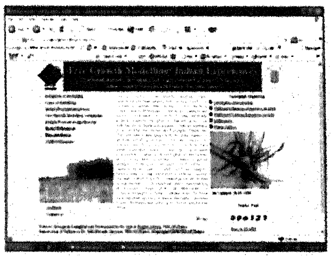
Website: http://mirror.iasri.res.in/net/tgm

Documentation, Analysis and Modelling of Eucalyptus based system for development of consolidated models at Zonal / National level



Thesis

Submitted for the award of

Doctor of Philosophy

in

AGROFORESTRY

(Tree Mensuration/Modelling)

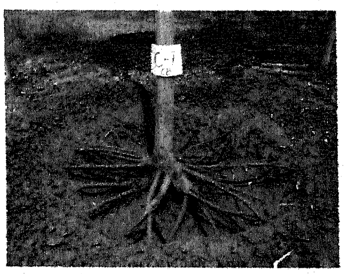
by

Nighat Jabeen

to

Institute of Agricultural Sciences

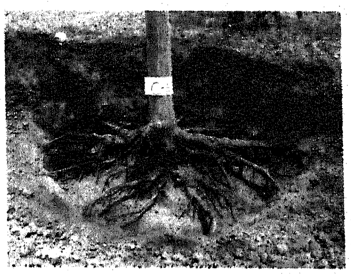
Bundelkhand University, Jhansi



Under the Supervision and Guidance of

Dr. Ajit

Senior Scientist



National Research Centre for Agroforestry (NRCAF)

Gwalior Road, Jhansi

2008

Declaration

*I hereby certify that the thesis entitled "**Documentation, Analysis and Modelling of Eucalyptus based system for development of consolidated models at Zonal/National level**" being submitted for partial fulfillment of Degree of Doctor of Philosophy (Agroforestry), Bundelkhand University, Jhansi (UP) is an original piece of work done by me under the supervision and guidance of **Dr. Ajit, Senior Scientist, NRCAF**, Jhansi and does not incorporate, without acknowledgment, any material previously submitted for a degree or diploma in any university, and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.*

Dated: 09|10|08

Nighat Jabeen

(Nighat Jabeen)

Gram : KRISHIVANIKI
Telephone (O): 0517- 2730214
- 2730213
- 2730479
Fax : 91-0517-2730364
E.mail : nrcaf@hubl.nic.in

राष्ट्रीय कृषि वानिकी अनुसंधान केन्द्र
National Research Centre For Agro-Forestry

भाकृअनुप
ICAR

Pahuj Dam, Jhansi Gwalior Road,
JHANSI-284003 (U.P.) India

पहुज बाँध, झाँसी ग्वालियर मार्ग,
झाँसी-284003 (उ.प्र.) भारत

NRCAF

Dated: 09-10-2008

Dr. Ajit
Senior Scientist
Email: umaajitgupta@yahoo.co.in
ajit@nrcaf.ernet.in

CERTIFICATE

*It is certified that this thesis entitled "**Documentation, Analysis and Modelling of Eucalyptus based system for development of consolidated models at Zonal/National level**" is an original piece of work done by **Ms. Nighat Jabeen** under my supervision and guidance for the degree of Doctor of Philosophy in Agroforestry, Bundelkhand University, Jhansi (India).*

I further certify that:

- *It embodies the original work of candidate herself.*
- *It is upto the required standard both in respect of its contents and literary presentation for being referred to the examiners.*
- *The candidate has worked under me for the required period at National Research Centre for Agroforestry, Jhansi.*
- *The candidate has put in the required attendance (more than 200 days) in the department during the period.*

09/10/2008

(Ajit)
Senior Scientist
NRCAF, Jhansi

राष्ट्रीय कृषिवानिकी अनुसंधान केन्द्र
निकट पहूज बाँध, ग्वालियर मार्ग, झाँसी - 284 003 (उ.प्र.)
National Research Centre for Agroforestry
Near Pahuj Dam, Gwalior Road, Jhansi - 284 003 (U.P.) India
Phones : 0510 - 2730214 (O), 2730366 (R), Fax : 0510 - 2730364,
E-mail : krishivaniki@mail.nrcaf.ernet.in, Gram : KRISHIVANIKI

डा. एस.के. ध्यानी
निदेशक
Dr. S.K. Dhyani
Director

Dated:09/10/2008

Certificate

*This is to certify that the thesis entitled **"Documentation, Analysis and Modelling of Eucalyptus based system for development of consolidated models at Zonal/National level"** submitted by **Ms. Nighat Jabeen** to the Department of Agroforestry, Institute of Agricultural Sciences, Bundelkand University, Jhansi for partial fulfillment for the award of the degree of Doctor of Philosophy in Agroforestry is a record of bonafide research work carried out by her at this centre under the supervision and guidance of Dr. Ajit (Senior Scientist). **Ms. Nighat Jabeen** has worked on this problem for a period of more than two years and the thesis is in my opinion worthy of consideration for the award of the degree of Doctor of Philosophy in Agroforestry in accordance with the regulation of this Centre. The results embodied in this thesis have not been submitted to any other university or institution for the award of any degree or diploma.*

10/10/08

Dr. V.K.Gupta
Principal Scientist and
Chairman of Higher Studies,
NRCAF, Jhansi

10/10/2008

Dr. S. K. Dhyani
Director,
NRCAF, Jhansi.

DIRECTOR
National Research Centre For Agro-Forestry,
JHANSI-284003

Bundelkhand University, Jhansi

Department of Agroforestry

CERTIFICATE

*This is to certify that thesis entitled "**Documentation, Analysis and Modelling of Eucalyptus based system for development of consolidated models at Zonal/National level**" has been carried out by Ms. Nighat Jabeen at **National Research Centre for Agroforestry, Jhansi** under the Supervision of **Dr. Ajit, Senior Scientist** and is submitted in partial fulfillment for the requirements of the Degree of Doctor of Philosophy in Agroforestry.*

13/10/08

(Dr. G.S. Pawar)
Head of Department
Institute of Agriculture Sciences
Bundelkhand University, Jhansi

13/10/08

(Dr. C. S. Dhanai)
Head
Division of Agroforestry
Bundelkhand University, Jhansi

Acknowledgement

There are lots of people I would like to thank for a multiplicity of reasons.

Firstly, I would like to thank my Supervisor, ***Dr. Ajit*** *(Senior Scientist, NRCAF, Jhansi). I could not have imagined having a better advisor and mentor for my Ph.D. and without his common-sense, knowledge, perceptiveness and cracking-of-the-whip, I would never have finished. Not only a great mentor, but he has also been a cornerstone in my professional development. Words fall short to describe what I learned from him. My deepest personal regards are due for him forever.*

I am also indebted to ***Dr. S. K. Dhyani, Director, NRCAF****, Jhansi, for providing me all the necessary facilities to complete this study in time. Thanks are due to* ***Dr. V.K.Gupta*** *(Principal Scientist) for permitting me to work at NRCAF, Jhansi.*

It is my profound privilege to verbalize my feelings of gratitude to the members of my Ph.D. advisory committee namely ***Dr. O. P. Chaturvedi*** *(Principal Scientist) and* ***Dr. A. K. Handa*** *(Senior Scientist), who monitored my work and took effort in reading and providing me with valuable comments on this thesis. Thanks are due to* ***Dr. Anil Rai*** *(Senior Scientist, IASRI, New Delhi) for permitting me to host Tree Growth Modelling website at IASRI server, New Delhi in time.*

I also express my gratitude and indebtedness towards ***Dr. C. S. Dhanai*** *and* ***Dr. G. S. Pawar*** *Head, Department of Agricultural Sciences, Bundelkhand University, Jhansi for their support to carry out this research work.*

I also wish to thank the scientific galaxy and administrative staff of NRCAF, particularly ***Dr. Rajeev Tiwari, Mr. Rajendra Singh*** *and* ***Mr. S. G. Dhamdere*** *for their prolific cooperation, inspiration, generous support, encouragement and countless ideas throughout my research work, when ever and where ever I needed.*

I would like to express my heartiest thanks to Sadiya for assisting in thesis typing and her family members for their affection and for never letting me feel that I am away from my parents.

I feel a deep sense of gratitude for my late father who formed part of my vision and taught me the good things that really matter in life. The happy memories of my father still provides a persistent inspiration for my journey in this life. Unfortunately, he is not here to share the moments with me, but I am sure he keeps an eye on me from heaven.

I express my sincere thanks and immense gratitude to my maternal uncles ***Mr. Ab. Rashid Bulla, Haji Khurshid Ahmad Bulla*** *and* ***Mr. Zahoor Ahmad Bulla*** *for their continued encouragement, affection and financial support during my study period.*

Great reverence and many many thanks to ***Mrs. Uma*** *(Technical Officer, NRCAF) who appeared to be my guardian here, I truly appreciate her expert guidance during awestruck times.*

My heartfelt thanks to ***Dr. Irshad*** *(Postdoctoral Fellow, University of Amsterdam) for his quick responses to my emails and ready to help attitude. Although we met only for a short period of time, but his enthusiasm for research always inspires me.*

Here, I would like to take an opportunity to acknowledge my friends, ***Fozia, Dr. Ruchi, Dr. Ritu, Munazah, Snober*** *and* ***Mussarat*** *for inspiring and motivating me throughout my research work. Warm thanks are extended to my roommates* ***Swati*** *and* ***Chanchal*** *(Senior Research Fellows) for good suggestions for this thesis and funny time together, which re-energized me at the times I needed most.*

With core of my heart, I am thankful to my dear mother, for her unconditional love and prayers; sister's ***Neelofar, Rehana*** *and* ***Nighat*** *whose continuous encouragement and support have been a source of inspiration in completion of this tough task.*

Thanks are due to ***Arvind*** *and* ***Ashok*** *for assisting in lab work and* ***Premnarayan*** *for assisting in fieldwork.*

Last but not the least; I am thankful to the Almighty, who has provided me sound health and strength to complete this work. What I am and what I would be, I owe to the Almighty for leading me the path of success.

Perhaps, I forgot someone... so, just in case: thank you to whom it concerns!

Nighat Jabeen

(Nighat Jabeen)

Preface

The present work is the outcome of the research carried out by me in the field of "mathematical modeling" of tree growth in agroforestry " registered at the Institute of Agricultural Sciences, Bundelkhand University Jhansi, under the guidance and supervision of Dr. Ajit, Senior Scientist at National Research Centre for Agroforestry (NRCAF), Jhansi, as a research scholar.

The work presented in the thesis entitled "Documentation, Analysis and Modelling of Eucalyptus based system for development of consolidated models at Zonal/National level" is based on my following research papers [copy of acceptance/publications attached in Annexure].

1. *"Generalized models for prediction of aboveground biomass for Eucalyptus species in India"*
   (Abstract accepted in Proceedings of National Symposium on "Agroforestry Knowledge for Sustainability, Climate Moderation and Challenges being conducted during 15th-17th December, 2008 being organized by National Research Centre for Agroforestry, Jhansi, India.

2. *"Designing and populating Tree Growth Modelling Website in Indian Perspective"*
   (Abstract accepted in Proceedings of National Symposium on "Agroforestry Knowledge for Sustainability, Climate Moderation and Challenges being conducted during 15th-17th December, 2008 being organized by National Research Centre for Agroforestry, Jhansi, India.

3. *"Comparison of initial growth and yield of Eucalyptus tereticornis clones under agroforestry system vis-à-vis block plantations in semi-arid conditions of India".*

(Paper was presented in the National Symposium on "Agroforestry for livelihood security, Environmental Protection and Biofuel Production" held at NRCAF, Jhansi during 16-18 Dec., 2006. In the ABSTRACT of National Symposium, 125-126 pp.

4. *"Statistical prediction of height through height-diameter models for Eucalyptus tereticornis in central India".*

   (Abstract was published in Proceedings of National Symposium on "Intensive Forest Farming: The State of the Art". held during Feb 12-14, 2008 organized by Punjab Agricultural University (PAU), Ludhiana. 146-147 pp).

5. *"Height estimation model for Eucalyptus tereticornis grown under semi arid conditions of India".*

   (Indian Journal of Agroforestry (2008). 10 (2): 34-39).

6. *"Growth model of Eucalyptus tereticornis and its validation through SPSS: a case study from semi-arid conditions in India".*

   (In Press: SPSS Analyst (2008)

A broad sketch of the thesis presentation is as follows.

Chapter-1 *entitled 'Introduction' primarily defines the term 'agroforestry', its various definitions, types (viz agrisilviculture, compact block plantations, agrihorticulture etc.), and its taxonomic classification. Moreover, the significance of Eucalyptus species has also been highlighted (a tree of great economic importance, as it is the basis of matchbox, pulp and paper production industry) along with its utilities (Eucalyptus trees are valued for their oil, gum and timber). Eucalyptus oil is used in medicine to treat many sicknesses such as infections, colds, flu, sore throats, bronchitis, and even some skin infections. The timber is claimed to be the strongest, densest and most durable in the world, used for the building of ships, railway ties, piers and telegraph poles. Eucalyptus oil is readily distilled from the leaves and can be used for cleaning, deodorizing, and in very small quantities in food supplements, especially cough drops and decongestants. Eucalyptus has been widely*

accepted by the farmers not only for pure plantations but also in agroforestry systems since Eucalyptus is one of the fastest growing species of the world with high productivity of 20-40 m^3/ha/yr, In view of the above, the necessity of Eucalyptus growth and yield modeling in the country has also been elaborated in this chapter.

Chapter-2 *entitled 'Materials and Methods' describes the complete details of the study site (rainfall and soil characteristics), experimental description (systems, clones, spacing etc.), growth observations (time, frequency and number of observations), harvesting details (above and below ground biomass, stem volume and index estimation representing the productivity). This chapter also includes the mathematical and statistical analysis details (including descriptive statistics viz mean, standard deviation, coefficient of variation, skewness, kurtosis etc, probability plots, scatter diagrams, fitting of the functions (parameter estimates with confidence interval, asymptotic standard error, R^2 value*). *Linear and non-linear models of regression analysis were fitted using various functions on the observed data. Residual diagnostics (mean residual, mean absolute residual) and various residual graphs pertaining to model validation procedures (viz the plot of residuals against their expected values for testing the normality of residuals, the auto correction plot of residuals for testing the independence of residual, the plot of residual vs. independent variate to confirm that the residual are not continuously being over/under estimated and the plot of residual against estimate to confirm that the residual have constant variance) were plotted to confirm that the regression pre-requisites are fulfilled and the models developed are statistically sound.*

Chapter-3 *entitled 'Collection and compilation of existing models on Eucalyptus spp. in India and their critical analysis' deals with the objective of performing a critical analysis of available models specifically on the basis of type of mathematical functions employed. The information have been compiled on the basis of various available parameters like species, state, measurable parameters like DBH (diameter at breast height 1.37m) and height range, spacing, age, type of equation, number of trees used for developing model etc. so as (i) to*

infer what extent of work on eucalyptus modeling has been reported in India (ii) to examine model accuracy and limitations of various equations used in eucalyptus modeling like linear, allometric, sigmoid etc. In addition to the critical analysis/interpretation of the existing work, further possible studies and implementations have also been proposed. A total of 11 equations for biomass and 26 equations for volume estimation could be traced from the published literature. The common phenomena associated with most of the linear growth models, is the negative estimation of size that is the dependent variate (volume, biomass) performed well with the observed range of independent variate viz DBH or D^2H, whereas the predictive values of size (volume, biomass) comes out to be negative for the lower range of independent variate as we start moving below the minimum observed value. The problem of extreme overestimation is associated with the allometric functions particularly just outside the observed higher range of independent variate, whereas the intricacy of constant estimation of size is observed with the S-shaped functions like Gompertz, Richards, Slodoba etc for the higher range of the observed independent variate like DBH or D^2H. A review of stem volume and biomass equation for eucalyptus in India is presented, with a brief introduction of different mathematical equations employed along with a critical discussion on their prediction capabilities and limitations.

***Chapter-4** entitled 'Modelling and comparison of growth attributes (height and dbh) of Eucalyptus tereticornis under different systems, spacing and clones' deals with the growth response of different parameters like tree height, diameter at breast height (DBH) of Eucalyptus tereticornis planted in different systems with different spacing [agrisilviculture (5x4m, 10x2m, 10x5m, 8x4m and 5x5m), compact block (3x3m and 2.5x2.5m), and boundary plantation (2.5m)] up to the age of 52 months evaluated in Bundelkhand region of Uttar Pradesh. At the age of 52 months, the Mean Annual Increment (MAI) of growth attributes under different systems were of height (3.27m) and DBH (3.41cm) in agrisilviculture, height (3.14m) and DBH (3.88cm) in compact block and height (3.62m), DBH (4.8cm) in boundary plantation respectively. The growth performance was statistically at par in all the three systems during the initial period (upto first three years of age)*

however significant and distinctly higher growth was recorded under the two agroforestry systems (AS, BP) as compared to monocropping system (CB) from the third year onwards. This chapter also interprets the effect of spacings, clones on tree growth attributes. The results suggests a positive effect of intercropping and wider spacing on height and diameter growth in eucalyptus based agrisilviculture system as compared to sole tree plantations in compact block plantation. This may be attributed to the fact that due to the crop management practices (fertilizers and irrigation given to the crop) in agrisilviculture system, the root system of tree component got developed at early stage as compared to compact block where there were no such management of crop and accordingly it took more time in compact block for proper development of root system and thus the growth picked up from second year onwards. Observations were recorded on tree height and DBH (diameter at breast height-1.37 m) to develop stand growth model. Model fitting was done using non-linear least squares algorithm. Schumacher, Richards and Allometric function have been attempted for fitting height-dbh models on the observed data, since these three functions are most preferred one's to fit height –diameter curves in majority of the published models. All the three functions shows comparable value of R^2 *however, by going through future prediction capabilities of tree height with respect to extrapolated DBH values, it is clear from the fitted graphs that only allometric function gives reasonably accepted predicted results, while other models leads to the problem of constant estimation of predicted height outside the observed range of independent variate. Residual diagnostics, through pertinent graphs, confirmed the accuracy of model estimation. A comparison of models for different systems (compact block, agrisilviculture and boundary plantation) is also discussed in this chapter. The developed functions are meant to form part of a system for long term forecasting of height-diameter growth curves.*

Chapter-5 *entitled 'Modelling and comparison of yield attributes (biomass and volume) of Eucalyptus tereticornis under two contrasting systems [agrisilviculture vs. compact block]' deals with the harvesting of Eucalyptus trees for development of models for growth and yield. A total of one hundred and twenty eight trees of Eucalyptus tereticornis (sixty four*

from compact block and sixty four from agrisilviculture plantation respectively) were harvested to develop regression equation for predicting standing tree's biomass (above ground, below ground, total biomass in kg/tree and biomass index in tons/ha/yr), volume (m^3/tree) and volume index (m^3/ha/year) with respect to tree diameter at breast height (DBH). A comparison has also been made, by developing separate prediction equations under the two systems, namely agrisilviculture and compact block plantation. DBH of harvested trees ranged from 0.95 to 13.69 cm and 0.96-19.43 cm, volume from 0.00034 to 0.116 m^3/tree and 0.00033 to 0.2219 m^3/tree, index from 1.08 to 53.08 m^3/ha/yr and 0.334 to 27.82m^3/ha/yr, total biomass from 0.319 to 106.81 kg/tree and 0.44 to 184.34 kg/tree, above ground biomass from 0.30 to 70.05 kg/tree and from 0.266 to 152.82kg/tree, below ground biomass from 0.109 to 36.76 kg/tree and from 0.113 to 46.52 kg/tree and height from 2.41 to 18.30 and 2.34 to 18.35 m under compact block and agrisilviculture plantation respectively. Component wise separate models were also developed for above ground biomass of the tree viz, leaf, branch and bole biomass. Tree wise volume and biomass values were observed to be on higher side in agrisilviculture plantation as compared to compact block, and this may be attributed to the fact that the nutrients and irrigation given to the crop in agrisilviculture system indirectly also helped the tree component and thus resulting in better growth attributes. Non-linear functions were fitted to the observed data and thoroughly evaluated through residual diagnostic which revealed that the variant of the allometric equations,

Total biomass = exp (6.21+77.56/(DBH)$^{1.5)}$ (R^2=0.92) and

Volume= exp (-0.70+73.75/(DBH)$^{1.5)}$ (R^2=0.96) under compact block and

Total biomass= exp (6.15+78.97/(DBH)$^{1.5)}$ (R^2=0.96) and

Volume= exp (-0.50+87.12/(DBH)$^{1.5)}$ (R^2=0.95) and under Agrisilviculture were statistically valid for the observed range of DBH (1-19cm), i. e. for early stage of tree growth under compact block and agrisilviculture plantations respectively for semi-arid conditions. These equations, though complex in nature and not as simple as the allometric ones, leads to logical and reasonable predictions. These equations may be used for estimation of plant biomass and volume from DBH measurements in permanent study sites

where destructive sampling is not possible, in addition to their utility for the policymakers, planners and research managers.

Chapter-6 *entitled 'Development of consolidated yield models (volume and biomass) of Eucalyptus spp. at national level by employing primary, secondary and simulated data' deals with the development and validation of generalized equations at the country level. In fact, most published biomass/volume equations were developed using trees sampled from specific study sites or from sites that represent small regions only. As a result use of existing volume/biomass equation with forest inventory data at large spatial scale is sometimes unreliable because the equations of previous studies may be site specific often disorganized and at times in consistant. Furthermore, unless an equation was developed exclusively for the species and study region of interest under conditions typical for the study site, it is impossible to know which equations to choose for a particular species and site. Accordingly, with the objective of developing site independent equations, we compiled all the published biomass/volume equation in India at one platform. These site specific equations were used to generate five equally space points (dbh points) and then the volume were computed. These points covered the range of dbh values specific to each regression and were used to generate a new simulated data set. This model ensures that each site-specific allometric equation was weighted equally in the formulation of the generalized equation. The simulated data set for AGB covered psedo harvested data from 4 states (Uttar Pradesh, Haryana, Karnataka, Tamil Nadu) and the volume-simulated data set encomposed harvested observations from 6 states (Uttar pradesh, Tamil nadu, Uttranchal, Rajasthan and Punjab). The simulated generalized equations are as follows:*

$Y=0.00093*(X)^{1.96}$ *for volume-dbh relationship*

$Y= 0.74*(X)^{1.81}$ *for AGB-dbh relationship*

These equations have been validated using geophysically and statistically independent data sets. The validity of the mathematical and physical assumptions used in developing a model and estimating the coefficients is less open to question if the model gives accurate

predictions of new data. In effect, the collection of new data provides an overall check on the entire model construction process.

Chapter-7 *entitled 'Development of Tree Growth Modelling Website in Indian Perspective and its launching on World Wide Web' has been designed with the basic objective of providing a platform where the user can have the basic concepts used in development of tree growth models at one end and the comprehensive collection of already developed model for a specific tree species at other end so as to use them directly for prediction purposes. At the initial phase of development of this site, we have concentrated on Eucalyptus species modelling. This website has been hosted at the server of IASRI (Indian Agricultural Statistics Research Institute), New Delhi and can be accessed at the URL: http://mirror.iasri.res.in/net/tgm/index.htm. This site is a unique collection of published biomass and volume equations, on Eucalyptus off course in Indian context only. The general portion of this site describes definition of modelling by various authors and principles of modeling; types of modelling describing about various types of models like descriptive models, prescriptive models, predictive models and simulation models; model development process depicting various steps of model development process like model estimation and model validation; tree growth modelling techniques describes essential steps of modelling tree growth like sampling of trees, measurement of height, diameter measurement, volume estimation, height measurement, estimation of biomass components etc.; models relevant to agroforestry provides the working outlines of the models relevant to agroforestry worldwide and finally have added tree growth modelling publication displaying a compilation of publication on tree growth modeling along with full length papers available in pdf format for downloading. This website has been designed to help for organizing, managing and sharing research information on Eucalyptus modelling in India. HTML, DHTML have been used for creating the dynamic pages of the database at the front end and the source codes written in HTML for designing the home page of Tree Growth Modeling Web site. The unified database has been equipped with interactive web pages to browse information on Eucalyptus introduction, modelling introduction, types of modelling, model development*

process, detailed information on biomass and volume models in India related to Eucalyptus species.

As the concluding remarks, in this thesis attempts have been made to transform the complex biological tree growth process into meaningful mathematical functions whose parameters have biological interpretation along with mathematical justification. These developed models are proposed to be used for interpolative as well as extrapolative predictions for the biomass, volume and index of standing tree (with out destructively harvesting the tree) by simply measuring a single and simply measurable variable namely the diameter at breast height. The models developed in this study will immediately provide us the values of biomass, volume and index of standing Eucalyptus trees by simply measuring the dbh values only. These models have been thoroughly validated for their prediction capabilities using mathematical and statistical tools.

Table of Contents

Pictorial depiction of the Thesis abstract: At a glance
(Objective wise achievements)

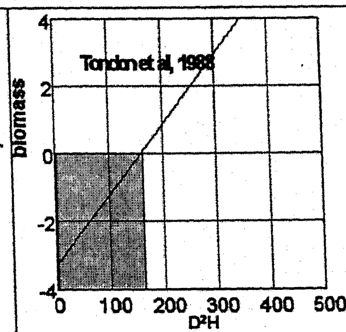
Objective-1: To collect, compile and collate all existing models on Eucalyptus spp in India at one platform in the form of a database.

Achievements: *A total of eleven biomass and twenty-six volume equations of eucalyptus spp.was compiled all over India. The information have been compiled on the basis of various available parameters like species, state, measurable parameters like DBH (diameter at breast height 1.37m) and height range, spacing, age, type of equation, number of trees used for developing model etc. so as to infer what extent of work on eucalyptus modeling has been reported in India. In addition to the critical analysis/interpretation of the existing work, further possible studies and implementations have also been proposed. The results are detailed in Chapter 3.*

S.No	Equation	Functions	Parameter values		R^2
			a	b	
1	$Y = a*(DBH)^b$	Allometric	0.26	2.17	0.70
2	$Y = a*(DBH)^b$	Allometric	0.42	1.96	0.82
3	$Y = a + b*(DBH)$	Linear	-149.98	13.39	0.80
4	$Y = a + b*(DBH)$	Linear	-376.31	28.85	0.66
5	$Y = a*(DBH)^b$	Allometric	0.14	2.41	0.97
6	$Log(Y)=a+b*Log(D^2H)$	Allometric	1.23	0.06	0.97
7	$Log(Y)=a+b*Log(D^2H)$	Allometric	-1.04	0.84	0.98
8	$Y= a + b*(D^2H)$	Linear	-3.39	0.02	0.95
9	$Y= a + b*(D^2H)$	Linear	-4.12	253.34	0.99
10	$Log(Y)=a+b*Log(D^2H)$	Allometric	-4.32	0.81	0.99
11	$Y= a+ b*(DBH)$	Linear	-635.41	35.73	0.95

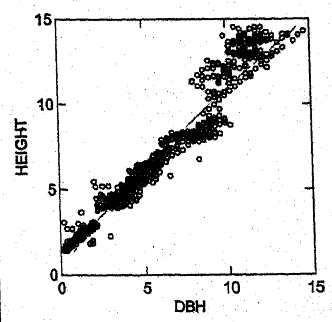
Objective-2: To perform a critical analysis of existing models.

Achievements: *Critical analysis of existing models of eucalyptus spp was done on the basis of type of equation used viz linear, sigmoid, allometric, parabolic etc, their problems were identified and the solution to these limitations have been proposed A review of stem volume and biomass equation for eucalyptus in India is presented, with a brief introduction of different mathematical equations employed along with a critical discussion on their prediction capabilities and limitations. The results are presented in Chapter 3.*

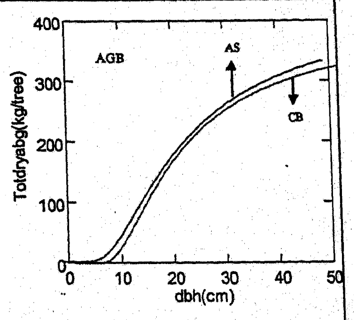


Objective-3: To compare the growth and yield in different systems/regions.

Achievements: Growth attributes (height-dbh): *Height-dbh growth was evaluated in three agroforestry systems viz agrisilviculture, compact block and boundary plantation and height-dbh models were developed and thoroughly validated. A comparison of models for different systems (compact block, agrisilviculture and boundary plantation) is also discussed in this chapter. The developed functions are meant to form part of a system for long term forecasting of height-diameter growth curves. The results are outlined in Chapter 4.*

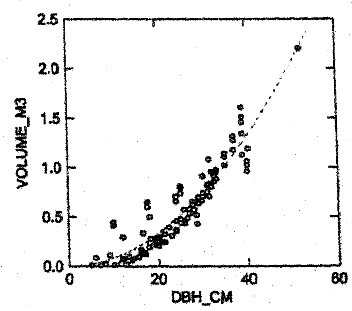


Achievements: Yield attributes (biomass and volume): *yield attributes were evaluated in two contrasting systems (agrisilviculture and compact block). Biomass and volume equations were also developed and thoroughly validated. A total of one hundred and twenty eight trees of Eucalyptus tereticornis (sixty four from compact block and sixty four from agrisilviculture plantation respectively) were harvested to develop regression equation for predicting standing tree's biomass (above ground, below ground, total biomass in kg/tree and biomass index in tons/ha/yr), volume (m^3/tree) and index (m^3/ha/year) with respect to tree diameter at breast height. The results are revealed in Chapter 5.*

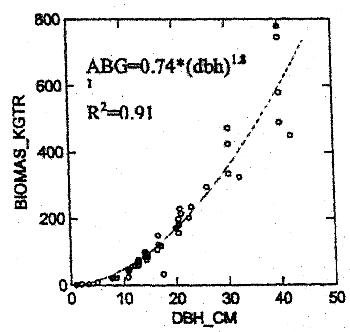


Objective-4: To develop consolidated models at broader level (local/regional or state/national level) by employing primary, secondary and simulated data.

Achievements: Volume simulation: *Consolidated model of volume of eucalyptus spp was developed at national level covering five states (Uttar pradesh, Tamil nadu, Uttranchal, Rajasthan and Punjab) and thoroughly validated with independent datasets. The simulated generalized volume is:* $Y=0.00093*(X)^{1.96}$.
The results have been portrayed in Chapter 6.

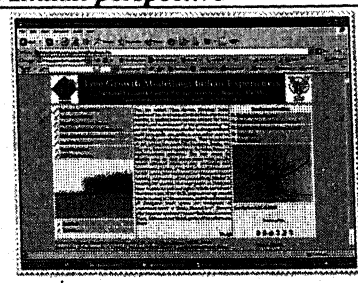


Achievements: Aboveground biomass simulation: *The simulated data set for AGB covered psedo harvested data from 4 states (Uttar Pradesh, Haryana, Karnataka, Tamil Nadu)The resulting above ground biomass equation is* $Y= 0.74*(X)^{1.81}$. *This equation has been validated using geophysically and statistically independent data sets. The validity of the mathematical and physical assumptions used in developing a model and estimating the coefficients is less open to question if the model gives accurate predictions of new data. In effect, the collection of new data provides an overall check on the entire model construction process. The results have been presented in Chapter 6.*



Objective-5: To develop and launch a "tree growth modelling" website in Indian perspective

Achievements: *The "Tree Growth Modelling website" been designed with the basic objective of providing a platform where the user can have the basic concepts used in development of tree growth models at one end and the comprehensive collection of already developed model for a specific tree species at other end so as to use them directly for prediction purposes. At the initial phase of development of this site, we have concentrated on Eucalyptus species modelling. This website has been hosted at the server of IASRI, New Delhi and can be accessed at the URL: http://mirror.iasri.res.in/net/tgm/index.htm. This site is a unique collection of published biomass and volume equations, on Eucalyptus, off course, in Indian context only. This website is compilation of biomass and volume equations along with their abstracts; modelling introductions, types, tree growth modelling process etc. The results are depicted in Chapter 7.*



Chapter-1
Introduction

Introduction

1.1 Agroforestry and Tree Growth Modeling: An overview

Agroforestry is one of the most widely practiced land-use system in the world, in which woody perennials (trees, shrubs etc.) are grown in association with herbaceous plants (crops, pastures) and/or livestock in spatial and temporal arrangement. In agroforestry there are both ecological and economic interactions between the woody and non-woody components of the system. Thus, the term 'agroforestry' encompasses a diverse set of integrated land use practices employed for variety of purposes. Trees play a crucial role in almost all terrestrial ecosystems and provide a range of products and services to rural and urban people. With clearance of natural forests for agriculture and other types of development, the economic and ecological benefits of trees could be sustained by integrating it into agriculturally productive landscapes through agroforestry.

Agroforestry combines agriculture and forestry technologies to create more integrated, diverse, productive, profitable, healthy and sustainable land use systems. Some important agroforestry practices include: agrisilviculture, agrihorticulture, sivipasture, alley cropping etc. According to the **Association for Temperate Agroforestry** - "Agroforestry practices are *intentional* combinations of trees with crops and/or livestock that involve *intensive* management of the *interactions* between the components as an *integrated* agro ecosystem". To be called agroforestry, a land use practice must satisfy all of these criteria: **Intentional**: combination of trees, crops and/or animals are intentionally designed and managed as a whole unit, rather than as individual elements that may occur in close proximity but are controlled separately; **Intensive**: agroforestry practices are intensively managed to maintain their productive and protective functions; these practices often involve annual operations such as cultivation and fertilization; **Interactive**: agroforestry management seeks to actively manipulate the biological and physical interactions between tree, crop and animal components. The goal is to enhance the production of more than one harvestable

component at a time, while also providing conservation benefits; **Integrated**: The tree, crop and/or livestock components are structurally and functionally combined into a single, integrated management unit. Integration may be horizontal or vertical, and above or below ground. Such interaction utilizes more of the productive capacity of the land and helps in balancing economic production with resource conservation.

Productive area available in the country is around 300 million ha of which 76.5 million ha is recorded forest area. Actual forest cover is 63.34 million ha of which 26.13 million ha is degraded. About 20 million ha is covered under private tree planting (agroforestry, farm forestry, social forestry and other plantations). In order to meet the increasing demand of our fast growing population, we would require to boost the production of food grain and fuel wood for human and green and dry fodder for livestock to the tune of 250,350 and 2085 million ton, respectively, besides 75 million m^3 of timber. Thus, to meet the gap between demand and supply of fodder, fuel and timber, the emphasis is to put on the integration of tree with agricultural crop, which is precisely agroforestry. Approximately 1.2 billion people, making 20% of the worlds population depend directly on agroforestry products and services in rural and urban areas of developing countries (Leakey and Sanchez, 1997) [109].

Almost, the entire 76 million ha recorded forest area is owned and managed by the State Governments in India. India occupying just 2.5 per cent of the land area of the planet earth has to support nearly 15 per cent of the world's human population and equally large, but mostly unproductive livestock. Therefore, the forests are under intense biotic pressures leading to degradation of forest resources. In India, 32 million ha of forest area has less than 40 per cent crown cover density. Forests in India have very low 65 m^3/ha growing stock compared to the world average of 110 m^3/ha. Likewise, mean annual increment is very low at 0.5 $m^3ha^{-1}yr^{-1}$ compared to the world average of 2.1 $m^3ha^{-1}yr^{-1}$ (Lal, 2008) [104].

Substantial improvement in productivity of forest resources and promotion of large scale farm-forestry plantations particularly of fast growing tree species are most essential to meet the basic needs for fuel-wood, timber and wood products and conservation of the natural resources on sustainable basis. The present forest resources with growing stock about 6, 414 million cubic mt, average volume of 61.72 cubic meter /ha and total annual increment of 87.62 million cubic meter cannot support the much needed demands of fuel wood, timber and raw material to industries and domestic use (Chauhan *et al.*, 2008)[39]. Therefore, more attention is required towards production forestry, which involves raising plantations of fast growing species under short rotation and intensive management. Short rotation forestry is a silvicultural practice by which high density sustainable plantations of fast growing tree species with annual woody production of at least 10 tonnes or 25 m^3 per hectare within a rotation period of less than 30 years are established (Verma, 2008)[219]. In India, industrial plantations of short rotation species like Eucalyptus, Poplars, Casuarinas have been raised for various purpose. The area under agroforestry with clonal Eucalyptus plantations is expanding fast in many states as farmers are expanding production of timber and pulpwood to meet the growing demand. Clonal Eucalyptus based agroforestry plantations are prevalent in many states like Andhra Pradesh, Orissa, Maharashtra, Punjab, Haryana, Uttrakhand and Uttar Pradesh. Many intercrops like oats, barseem, cowpeas, ginger, wheat, blackgram, turmeric and millets have been successfully raised during the Rabi and Kharif season. Large-scale eucalyptus plantations have been raised on forest and farm lands, community lands, road/rail/canal strips. Intensively managed plantations based on genetically improved clonal planting stock and supported with sound silvicultural practices can achieve productivity levels of 20-40 $m^3ha^{-1}yr^{-1}$ even on the marginal lands. Significant improvements in quality of produce and reductions in per unit production costs have also been possible with the use of true to type, uniform and genetically improved clonal planting stock.

Eucalyptus clones like C3, C6, C7, C10 and C27 developed at Indian Tobacco Corporation (ITC) Bhadrachalam, Andhra Pradesh formed the basis of initial clonal plantations since 1992.Average productivity of commercial clones is around 20 to 25 m^3 ha^{-1} yr^{-1} under unirrigated conditions. However, many farmers have achieved record growth rates of more than 50 m^3 ha^{-1} yr^{-1} making farm forestry an economically attractive land use option with better net returns compared to traditional crops. (Lal, 2007)[103].

There are almost 600 species of Eucalyptus, mostly native to Australia. Eucalyptus was first introduced in India as early as the year 1790, at nandi hills, Mysore. In 1843, it was successfully introduced in nilgiri hills in south India. However regular plantations were taken up only in 1851. Among the many spp viz., *Eucalyptus rudis, E. camaldulensis* (Red gum), *E. citriodora* (Lemon-scented gum), *E. coccifera* (Tasmanian snow gum), *E. dalrympleana* (Mountain gum), *E. ficifolia* (Red flowering gum), *E. globulus* (Tasmanian blue gum), *E. gunnii* (Cider gum), *E. johnstonii* (Yellow gum), *E. leucoxylon* (White ironbark), *E. parvifolia*, *E. pauciflora* subsp. *niphophila* (Snow gum), *E. perriniana* (Spinning gum), *E. sideroxylon* (Red ironbark), *E. urnigera* (Urn gum), the nandi provenance of *Eucalyptus tereticornis*, popularly known as mysore gum is most promising. Synonyms include: *Eucalyptus tereticornis* var. *pruiniflora* (Blakely) Cameron; *Eucalyptus insignis* Naudin; *Eucalyptus populifolia* Desf. ; *Eucalyptus subulata* Schauer ; *Eucalyptus umbellata* (Gaertn.) Domin nom. illeg. ; *Eucalyptus umbellata var. pruiniflora* Blakely. There have also been numerous subspecies and varieties published, but the only one that remain current is *E. tereticornis* subsp. *mediana* and the autonym *E. tereticornis* subsp. *tereticornis.* Eucalyptus species is of great economic importance, as it form the basis of matchbox, pulp and paper production industries and valued for oil, gum and timber. Eucalyptus oil is used in medicine to treat many sicknesses such as infections, colds, flu, sore throats, bronchitis, pneumonia, aching, stiffness, neuralgia and even some skin infections. The timber is claimed to be the strong, dense and most durable in the world and used for the

building of ships, railway ties, piers and telegraph poles. Eucalyptus oil is readily distilled from the leaves and used for cleaning, deodorizing, and in very small quantities in food supplements, especially cough drops and decongestants. *E. tereticornis* plantations accounted for 415000 ha out of the total area reported in India by 1974. It grows to a height of from 20 to 50 metres, and dbh of upto 2 metres. In general, *E. tereticornis* is fairly free of pests and except termites attack on young plants if insecticide not used while planting. In India, the most serious disease has been the canker caused by *Corticium salmonicolo*. This species has been the most widely used species for raising plantations in denuded and barren areas and also for replacing low value natural crops. This species was first raised on large plantation scale in Karnataka state in 1952 and experiments were subsequently taken up in other states. Extensive plantations were undertaken in Punjab and Haryana under agroforestry to meet the demands of fuel wood, small timber and pulpwood etc.

Botanical Classification

Kingdom:	Plantae
Division:	Magnoliophyta
Class:	Magnoliopsida
Order:	Myrtales
Family:	Myrtaceae
Genus:	*Eucalyptus*
Species:	***E. tereticornis***

1.2 Present state of knowledge

Eucalyptus has been widely accepted by the farmers not only in pure plantations but also along with crops in agroforestry because of its short rotation and high economic return. Eucalyptus has also been recommended as one of the six tree species by the Planning Commission through its report on "Task Force on Greening India" (Planning Commission, 2001)[143].

The yields that have been obtained in existing short rotation fast growing plantations (often with exotic species) have been many times greater than those in natural forests. There are many documented reports of the growth and biomass of tropical plantation species in relation to adjacent native forest but there are relatively fewer reports of biomass response to experimental manipulation of silvicultural inputs. Various aspects of Eucalyptus have been studied and published in recent years viz Optimum spacing (Rawat, 1990[157], Naugraiya and Puri, 2001[131]); Antibacterial activity and gastro protective properties (Nair *et al.*, 2008[129]; Singh and Sharma 2005[181]; Cermelli *et al.*, 2008[33]; Adeniyi *et al.*, 2006[1]); Diversity of termite (Varma and Saran, 2007[215]); Sustaining productivity over multiple rotations (Sankaran *et al*, 2007[170]); Height-growth and site index equations (Tewari *et al.*, 2007[206]); Utilisation in making base paper of playing cards (Dutt *et al.*, 2007[50]); Nutrient dynamics through litterfall (Rana *et al.*, 2007[153]; Turner and Lambert, 2008[214]; Guo *et al.*, 2006[66]); Carbon sequestration potential (Sudha *et al.*, 2007[193]; Stape *et al.*, 2008[190]); Bioremediation (Maiti, 2007[113]); Transpirational water loss (Kallarackal and Somen, 2008) [89]; Fungicidal and pesticidal properties (Tripathi *et al.*, 2008[213]; Richard, 2006[164]); Electricity generation (Amatayakul and Azar, 2003[9]) and many more.

In recent years there has been an increase in the number on studies of forest biomass (Munoz *et al.*, 2008[126]; Mani, and Parthasarathy, 2007[115]; Harmand *et al.*, 2004[70] ; Gill *et al.*, 2001[62]; Rana *et al.*, 2002[152] ; Mishra and Nayak, 2000[122]).

Thakur and Singh, 2005[209], studied growth (diameter, height and survival percentage) and biomass estimates of *Eucalyptus tereticornis* plantations of different provenances and reported that highest aboveground biomass was observed in Raipur provenance (21.69 t/ha). Higher proportion of aboveground biomass was allocated to bole (60.4-63.3%) followed by branch (12.01-14.46%) and foliage (4.14-4.81%).

Turner and Lambert, (2008)[214] quantified above ground tree biomass of *Euclayptus grandis* and *E. pilularis* at north coast New South Wales and reported that maximum aboveground tree biomass of *E. grandis* and *E. pilularis* was 14.62t/ha/yr at 27 yrs and 8.18 t/ha/yr at 33 yrs, respectively. The estimated maximum current annual accumulation of tree biomass was 16.4 t/ha/yr at 5 yrs and 15.7t/ha/yr at 7 yrs of age for *E. grandis* and *E. pilularis* respectively.

Datta and Singh, 2007[43] reported a timber volume of 19.68 m^3/ha/yr for *Eucalyptus hybrid* at a spacing of 3mx3m at 16 yrs of age with MAI of $1.77 x 10^{-2} m^3$/ha/yr.

Tandon *et al.*, (1993)[198], evolved biomass equations for 4, 6, 8 and 10 year old plantations of *Eucalyptus hybrid* from Haryana state. Biomass estimates were made using the stratified tree technique: a total of 17 sample trees were harvested, and measurements were made on height, dbh along with aboveground biomass (stems, bark, leaves and twigs). Various models were used for the biomass estimates, and those using diameter at breast height (DBH) as independent variable were selected. Biomass = $0.1353357*(DBH)^{2.416484}$ has been reported to be the best function. Regressions were derived for total biomass, and for each component separately. Density and total aboveground standing biomass of the plantations were 1805, 1116, 844 and 955 stems/ha and 20.1, 34.6, 88.7 and 137.7 t/ha, for 4, 6, 8 and 10 year old plantations respectively, mean DBH range for plantations of different ages were 3.3-20.29 cm. Validation of model was not attempted. Biomass components also increased with age, however, while stem biomass increased with increasing diameter and age from 54 to

78%, the per cent allocation for biomass of the other components decreased proportionately.

Gill and Ajit (2005)[61], compared the growth characters of the twelve multipurpose tree species including *Eucalyptus tereticornis* under semiarid conditions and reported that it maintained its superiority over remaining trees for growth characters like plant height and diameter. Moreover, the growth attributes were better in agrisilviculture system as compared to compact block.

Patil *et al.*, (2000)[141], studied the growth and yield of eucalyptus at the age of 17 years and reported that the height was 20.4m and timber volume was 65.6 m^3 / ha that led to the income of Rs 67,883/ha/yr.

Height-diameter curves have been developed frequently in forestry studies by several authors (Sharma and Parton, 2007[175]; Lootens *et al.*, 2007[111]; Castedo *et al.*, 2006[30]; Reed *et al.*, 2003[161]; Mehtatalo, 2005[121]; Inoue and Yoshida, 2004[78]; Sochacki *et al*, 2007[188]). Bachpai *et al.*, (2005) [15] developed multiple regression models for prediction of height using dbh and age for *Bambusa tulda* Roxb. plus clumps in regions of Assam and Meghalaya. Tewari and Gadov, (2003)[203] developed a height-diameter relationship for *Prosopis cineraria* for the hot arid areas of India. Tewari *et al.*, (2002) [207], have attempted height-age and diameter-age models for irrigated plantations of Rajasthan and Soarces and Tome, (2002)[185], have developed height-diameter equation for *Eucalyptus* in first rotation.

Ajit *et al.*, (2006)[6], fitted non linear functions for Above Ground Biomass (AGB) to the observed data and thoroughly evaluated the model using through residual diagnostic which revealed that the allometric equations: $AGB=0.264* (DBH)^{2.173}$ and $AGB =0.421* (DBH)^{1.967}$ were statistically valid for a wide range of DBH (1-40) under

energy and boundary plantations, respectively in semi arid conditions for estimation of above ground tree biomass.

Harvesting of fast growing tree species at young age is now a days increasing due to pressing demands of wood in paper and wood industry for manufacturing plywood, fiberboards, match sticks, packing cases etc. This has led to change in wood utilization pattern. As a result, growth and yield models at early phase of tree development are viewed as an important research and management tool to estimate the values of volume, biomass and height of standing growing stock without destructive sampling. Models, hough very few as discussed above, have been developed for volume / biomass rediction, but these are region / location specific and moreover utilize numerous input ariables. Thus most of the models are complex in nature and consequently cannot be irectly used.

ree growth models have ability to predict the future yields and provide chance to xplore silvicultural options. They provide an efficient way to prepare resource recasts to explore management options and silvicultural alternatives. Models are equently used to visualize cause-effect of relationships to explain and anticipate the havior of systems. Models may be descriptive or predictive. A mathematical model is e a descriptive model, uses mathematical relationships that are more concise and less nbiguous than natural language. A tree-stand growth model is an abstraction of the utral dynamics and generally refers to interlinking of series of mathematical uations related to component growth as per an assumed flow chart of the system.

model is considered as simplified representation of reality. Many complex eractions and results are depicted with simplicity to reach a decision. It is expected to a good representation of those factors that influence production and management. delling provides tools to predict the consequences of an action that would be erwise expensive, difficult or destructive but is essential for launching a programme.

It also helps in understanding the needs of inputs to optimize the desired output and system sustainability. Models can be broadly classified into two categories namely linear and non-linear. Linear ones, though simple to fit and easy to use, do not in general properly mimic the real tree growth. On the other hand, non-linear ones more closely approximate the real biological tree growth process. Accordingly, the non-linear functions have been addressed, attempted and analyzed for this work.

Modelling has been used in natural sciences since centuries in one way or the other. However, system modelling as a discipline in itself established in the current century only. Models have been built in the physical, biological and social sciences. The building blocks for these models have been taken from calculus, algebra, statistics, geometry, probability and nearly every other field within mathematics. Various researchers have defined modelling in their own way, some prominent and worth mentioning are:

Mclone and Andersons, 1976[120] described modelling as the representation of our so called 'real-world' in mathematical terms so that we may gain a more precise understanding of its significant properties and which may hopefully allow some form of prediction of future events.

Hall, 1963[68] said "The goal of modelling is to understand reality mathematically".

Meyer, 1985[119] defined model to be an object or concept that is used to represent something else. It is in reality scaled down and converted to a form that we can comprehend. He further adds that a mathematical model is a model expressing mathematical concepts, having constants, variables, functions, equations, inequalities, etc.

Agroforestry modelling is a complex process that essentially involves at least two elements viz tree and crop, where tree is the long term and crop is the short term component. Agroforestry models, usually, predict tree growth and yield and the reduction/enhancement in crop yield as influenced by the tree component in temporal and spatial sequence. Models providing the most accurate prediction of height include basal area, trees/ha, dominant stand height, and diameter at breast height (Sharma and Parton, 2007)[175], whereas the models for prediction of biomass components or volume utilizes dbh(D) or height (H) or a combination say D^2H as independent variate.

A model is a way to represent, in mathematical terms, the relationship that exists in the real world. we can use models to describe what might happen in future based on certain conditions and assumptions. Intuitively we use models every day although we probably do not think about it consciously. For example, you know how much time you must allow to get home from your work place. If you choose a mini bus it usually requires less time than a regular bus. If you wanted you could have described that relationship with a mathematical model. Models are handy tools because they parallel the way we human beings think. Once you describe relationships that exists in the real world you can then extend the model you developed to predict what will happen if those relationships does not remain the same. Thus, modelling is done to aid the conceptualization and measurement of complex systems and some times to predict the consequences of an action that would be expensive, difficult or destructive otherwise to do with the real system. Thus, you can easily do "what-if" modeling. Just change your model assumptions and conditions, repeat the calculations, and observe the predicted outcomes.

Although review of literature, described in the preceding sections reveals that although model have been attempted for eucalyptus based systems in India, but they are few in number and of limited predictive use since (1) they generally utilize data pertaining to a single harvesting only (2) they are strictly location specific (3) validation of the models have not been attempted in most of the published papers. Accordingly to overcome

these limitations and to fulfill these research gaps, this study was initiated with the following objectives

Objectives

The overall objective of this study was to develop growth models that will hold good at zonal / national level for prediction of growth and biomass of *Eucalyptus tereticornis* plantations. Specific objectives were:

1. To collect, compile and collate all existing models on *Eucalyptus* spp in India at one platform in the form of a database.
2. To perform a critical analysis of existing models.
3. To compare the growth and yield of *E. tereticonnis* in different systems/regions.
4. To develop consolidated models of Eucalyptus at broader level (local/regional or state/national level) by employing primary, secondary and simulated data.
5. To develop and launch a "tree growth modelling" website in Indian perspective.

Chapter-2

Materials and Methods

Materials and Methods

2.1 Study site

The experiment was conducted at the Central Research Farm of National Research Centre for Agroforestry, Jhansi which is located at an elevation of 300 m above sea level and is situated between 24°11' N latitude and 78°17' E longitude having tropical semi arid climate with mean annual rainfall of 900 mm. More than 75% of the rainfall is received during monsoon season (last week of June to first week of September). Mean maximum temperature ranges from 47.4° C (June) to 23.5° C (December) and mean minimum temperature from 27.2° C (June) to 4.1° C (December). The soil of the experimental area is sandy loam with low organic carbon, nitrogen, phosphorous and medium to high in potassium.

2.2 Experiment description

The study was initiated in August, 2003 with the objective of studying the structure, biomass, productivity and modelling the growth of Eucalyptus based systems. The experiment was laid with three systems of *Eucalyptus tereticornis* namely agrisilviculture (AS), block plantation (CB) and boundary plantation (BP). Tree spacings considered in agrisilviculture are 5x4 m, 10x2 m, 10x5 m, 8x4 m and 5x5 m; compact block are 3x3 m and 2.5x2.5 m and boundary plantation is 2.5 m. Wheat and Black gram were grown in the interspaces during Rabi and Kharif seasons respectively under boundary plantations and agrisilviculture systems. Four Eucalyptus clones namely C-3, C-6, C-7 and C-10 were obtained from ITC, Bhadrachalam, Andhra Pradesh and planted in field during August, 2003.

2.3 Growth observation

The growth observations were recorded after every six months in the third year (2006) and fourth year (2007). Observed parameters include total height, DBH (Diameter at breast height), CD (Collar diameter) and canopy of the each individual tree. A total of 882 trees from the complete experiment were measured for the third year. However,

from fourth year only 862 trees were marked from the whole experiment for further growth observation.

Time schedule for growth observation in third year. (2006).

1. June-2006
2. December-2006

Time schedule for growth observation in fourth year. (2007).

1. June-2007
2. December-2007

2.4 Volume-biomass studies

Eight trees (two from each clone) were selected from compact block plantation of spacing 2.5x2.5m and other eight were selected from agrisilviculture (new plantation at the spacing of 5x4m).

Time schedule for harvest data

1. September-2006
2. March-2007
3. September-2007
4. March-2008

2.4.1 Above Ground Biomass components

Trees were felled 2-3 cm above the ground. The diameter at breast height (DBH) was recorded by measuring vernier calipers. The total height of felled tree was measured by tape in meter. The felled tree was divided into one meter long pieces starting from the toe to the top of the tree. The leaves were separated and the fresh weights were recorded in kg/tree for leaves, branches and main bole for every one-meter piece. Fresh samples were collected for leaf, branch and bole, oven dried at 70^0c till constant weight and finally dry matter percentages were computed. Fresh weights were multiplied by dry

matter percentages to obtain the oven dry biomass of leaf, branch and bole separately. The three components were added to yield the total above ground dry biomass (AGB).

2.4.2 Below Ground Biomass components

For below ground observations, root system were harvested carefully and biomass of main root, primary root, secondary root and fine root were measured separately. Fresh samples for these components were collected and oven dried at 70^0c till constant weight and finally dry matter percentage were computed. Fresh weights were multiplied by dry matter percentages to obtain the oven dry biomass of all components separately. The total components were added to get the total below ground dry biomass (BGB).

2.4.3 Over-dry Weight

Over-dry weight was obtained by putting sample in an oven at 70^0 Celsius for 48 hours until there were no more changes in weight. Over-dry weight to fresh weight ratio was used to convert fresh weight to oven-dry weight.

- ***Foliage Sample*:** All foliage (tree wise) were separated and weighed for fresh weight. A representative sample for each harvested tree, were collected and sealed in a plastic bag. This sample was taken to the research laboratory to obtain oven-dry weight. These provided an oven-dry weight to fresh weight ratio. This ratio was used to obtain oven-dry weight of foliage fresh weight for harvested trees.

- ***Branch Sample*:** All branches of a tree were weighed to obtain fresh weight. A representative sample for each harvested tree, were collected and sealed in a plastic bag. This was taken to a research laboratory to obtain over-dry weight, which provided an oven-dry weight to fresh weight ratio. This was used to obtain oven-dry weight of branch fresh weight of all harvested trees.

➢ ***Bole Sample*:** For dry biomass estimation purposes, felled trees were divided into one-meter logs and these meter logs were weighed to obtain fresh weight for each tree. Samples were collected from the top, middle, and bottom sections for each tree. Finally the dry matter percentage was multiplied by fresh weight to obtain oven dry weights for each tree.

2.4.4 Tree Volume Estimation

Tree volumes can be estimated in a number of ways. Most method estimate different portions of the tree volume using different formulas. Fig. 1 below indicates the most commonly used formula for each portion of a tree.

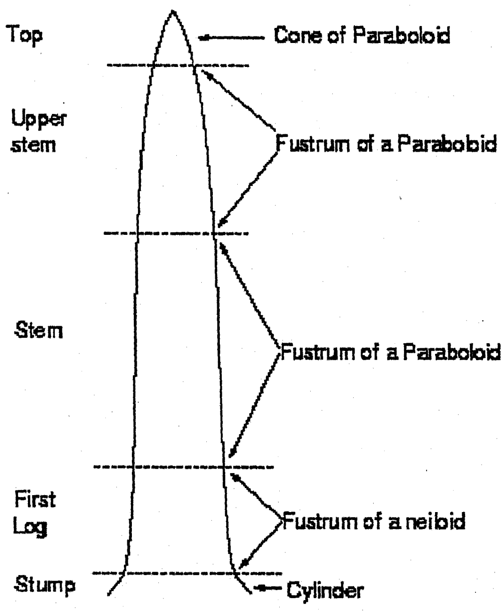


Fig.1: Volume formulas suggested by portion of the stem.

Each of these sections of the stem can be estimated using one of four basic equations;

Cylinder - The cylinder formula is the simplest of all the formulas. It requires only the area of one end and the length of the cylinder.

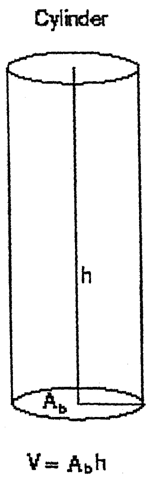


Fig. 2: The formula for the area of a cylinder

Cone

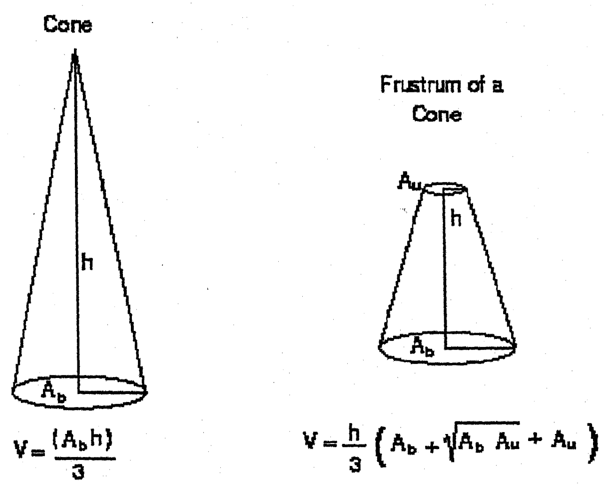
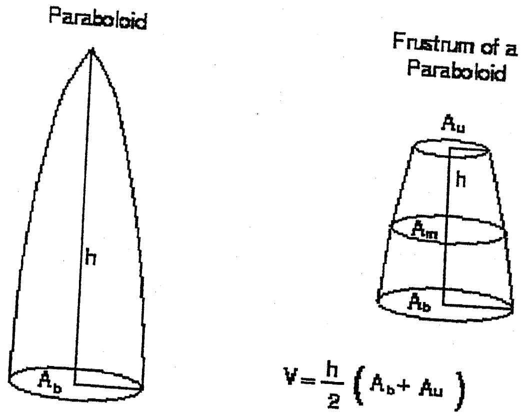


Fig. 3: The formula for a cone and the frustum of a cone.

- **Paraboloid**



$$V = \frac{(A_b h)}{2}$$

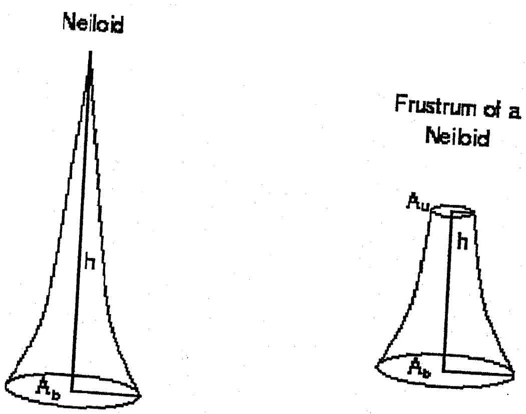
$$V = \frac{h}{2}\left(A_b + A_u\right) \quad \text{Smalian's formula}$$

$$V = h\left(A_m\right) \quad \text{Huber's formula}$$

$$V = 1/6\,(A_b + 4A_m + A_u).h \quad \text{(Newtons Formula)}$$

Fig. 4: The formula for a paraboloid and the frustum of a paraboloid.

- **Neiloid**



$$V = \frac{(A_b h)}{4}$$

$$V = \frac{h}{4}\left(A_b + \sqrt[3]{A_b^2 A_u} + \sqrt[3]{A_b A_u^2} + A_u\right)$$

Fig. 5: The formula for a neiloid and the frustum of a neiloid.

For estimating the volume, observation of lower and upper diameter was recorded for every one-meter piece of bole of tree.

In present study we used Newton's Formula, (by Husch *et al.*, 1982[76], Forest mensuration, IIIrd Edition) for estimating individual tree volume.

$$V = \frac{1}{6}(A_l + 4A_m + A_u) * h$$

$$or \quad V = \frac{1}{6}(\pi r_l^2 + 4\pi r_m^2 + \pi r_u^2) * h$$

$$= \frac{1}{6}(3.14 * (\frac{d_l}{2})^2 + 4 * 3.14 * (\frac{d_m}{2})^2 + 3.14 * (\frac{d_u}{2})^2) * h$$

$$= \frac{1}{6}(\frac{3.14}{4} * d_l^2 + 4 * \frac{3.14}{4} * d_m^2 + \frac{3.14}{4} * d_u^2) * h \qquad [\text{'h' in meter,'dbh' in cm}]$$

$$= \frac{1}{6} * 0.784 * (d_l^2 + 4d_m^2 + d_u^2) * h$$

$$= \frac{1}{6} * 0.784 * ((\frac{d_l}{100})^2 + 4(\frac{d_m}{100})^2 + (\frac{d_u}{100})^2) * h \qquad [\text{ Now 'h' and 'dbh', both are in mts}]$$

$$= \frac{1}{6} * 0.784 * (\frac{d_l^2 + 4d_m^2 + d_u^2}{100 * 100}) * h \qquad [1\text{m} = 100\text{cm}]$$

$$= \frac{1}{6} * \frac{0.784}{100 * 100} * (d_l^2 + 4d_m^2 + d_u^2) * h$$

$$= \frac{1}{6} * 0.0000784 * (d_l^2 + 4d_m^2 + d_u^2) * h$$

$$= \frac{h}{6} * 0.0000784 * (d_l^2 + 4d_m^2 + d_u^2)$$

$$= \frac{2}{6} * 0.0000784 * (d_l^2 + 4d_m^2 + d_u^2) \qquad [\text{for our case h} = 2\text{m, i.e log of 2mts}]$$

$$= \frac{1}{3} * 0.0000784 * (d_l^2 + 4d_m^2 + d_u^2)$$

$$\text{V} = 0.0000261 * (d_l^2 + 4d_m^2 + d_u^2) \qquad [where\ d_m = \frac{d_l + d_u}{2}]$$

Where V-volume of the log (to be calculated)

where height in meter, diameters (i.e. d's) in centimeter and resulting volume in m^3 in m^3(Cubic meter)

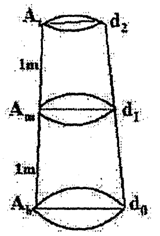


Fig.6: Sectional piece of the main bole for computation of volume

For calculating the volume of upper end of tree the formula for parboiled were used which is $Volume = (0.00003927) * (d^2 l)$

$$
\begin{aligned}
\text{Volume of Paraboloid} &= \frac{1}{2} * A * l \\
&= \frac{1}{2}(\frac{\pi}{4} * d^2) * l \qquad [\text{Area} = \pi\ r^2] \\
&= \frac{1}{2}(\frac{3.14}{4} * d^2 * l) \\
&= \frac{1}{2}(0.784 * d^2 * l) \qquad [l \text{ in mts, d in cms}] \\
&= \frac{1}{2}(0.784 * (\frac{d}{100})^2 * l) \quad [1\text{m} = 100\text{cm}] \\
&= \frac{1}{2}(0.0000784 * d^2 * l) \\
&= 0.00003927 * d^2 * l
\end{aligned}
$$

Where d is the lower diameter and l is the length of remaining part of the tree

2.5 Index/Productivity

The formula for index calculation

Index = (volume of one tree) *(number of tree in one hectare)

since 1hactare = 10,000 m^2

Number of tree in one hectare = 10,000/(spacing m^2)

$$Volume\ Index = \frac{volume(m^3\ /\ tree) * 10{,}000}{spacing(mxm) * age(yrs)}(unit{:}m^3\ /\ ha\ /\ yr)$$

$$Biomass\ productivity = \frac{biomass(kg\ /\ tree) * 10{,}000}{spacing(mxm) * age(yrs) * 1000(\text{to convert into tons})}$$

$$= \frac{Biomass(kg\ /\ tree) * 10}{spacing(mxm) * age(yrs)}(unit{:}tons\ /\ ha\ /\ yr)$$

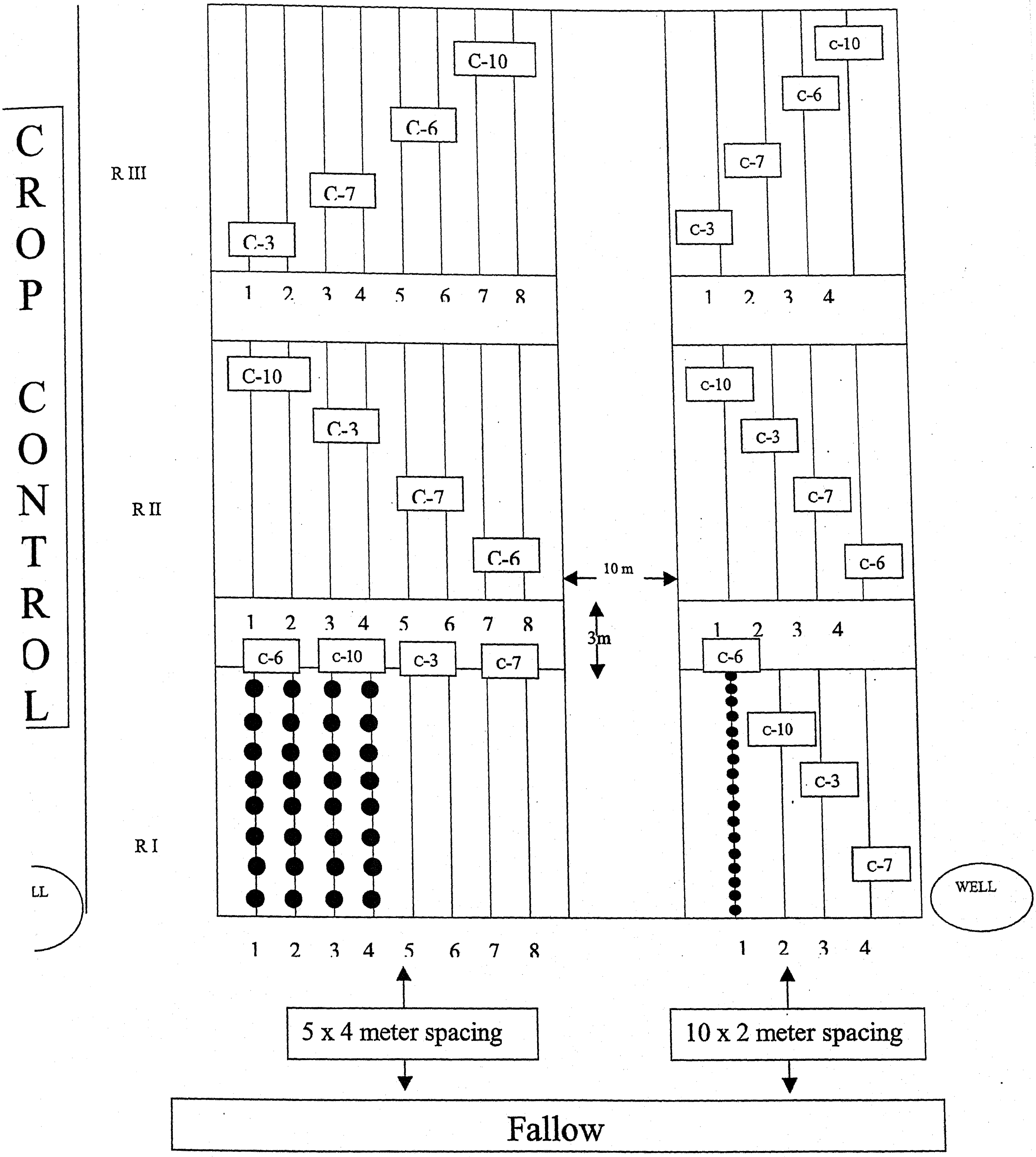
2.6 Statistical Analysis

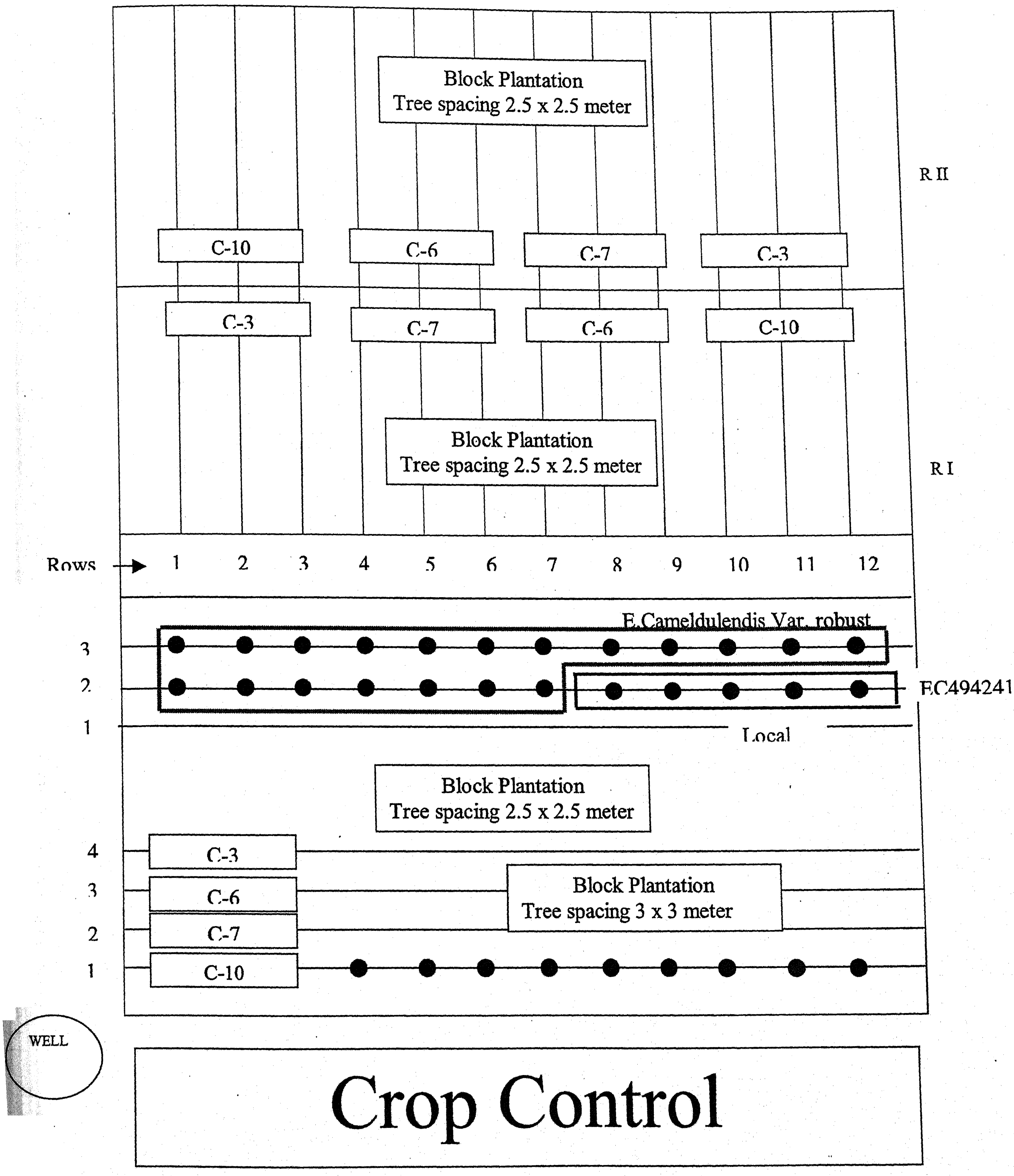
The statistical analysis of data were performed using SYSTAT software version 12.01.04 (Wilkinson and Coward, 2007[225]). The statistical analysis includes descriptive statistics (viz mean, standard deviation, coefficient of variation, skewness, kurtosis etc), probability plots, scatter diagrams, fitting of the functions (parameter estimates with confidence interval, asymptotic standard error, R^2. value). Linear and non-linear models of regression analysis were used for fitting various functions on the observed data. Residual diagnostics (mean residual, mean absolute residual) and various residual graphs pertaining validation procedures (viz the plot of residuals against their expected values for testing the normality of residuals, the auto correction plot of residuals for testing the independence of residual, the plot of residual vs. independent variate to confirm that the residual are not continuously being over/under estimated and the plot of residual against estimate to confirm that the residual have constant variance) were prepared using various graphical options in SYSTAT 12 (systat Inc@2007, CA, USA).

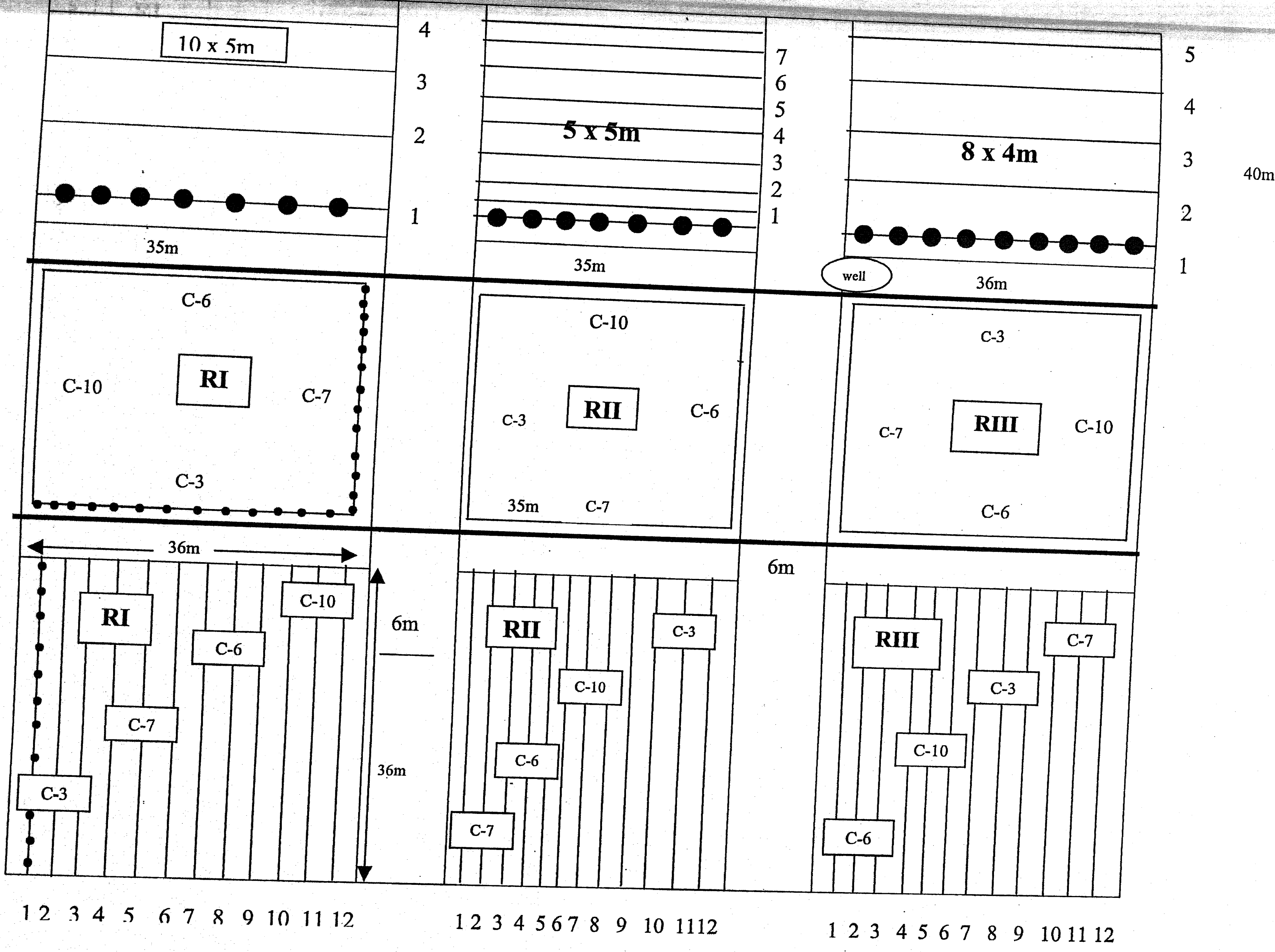
2.7 Field experiment layout

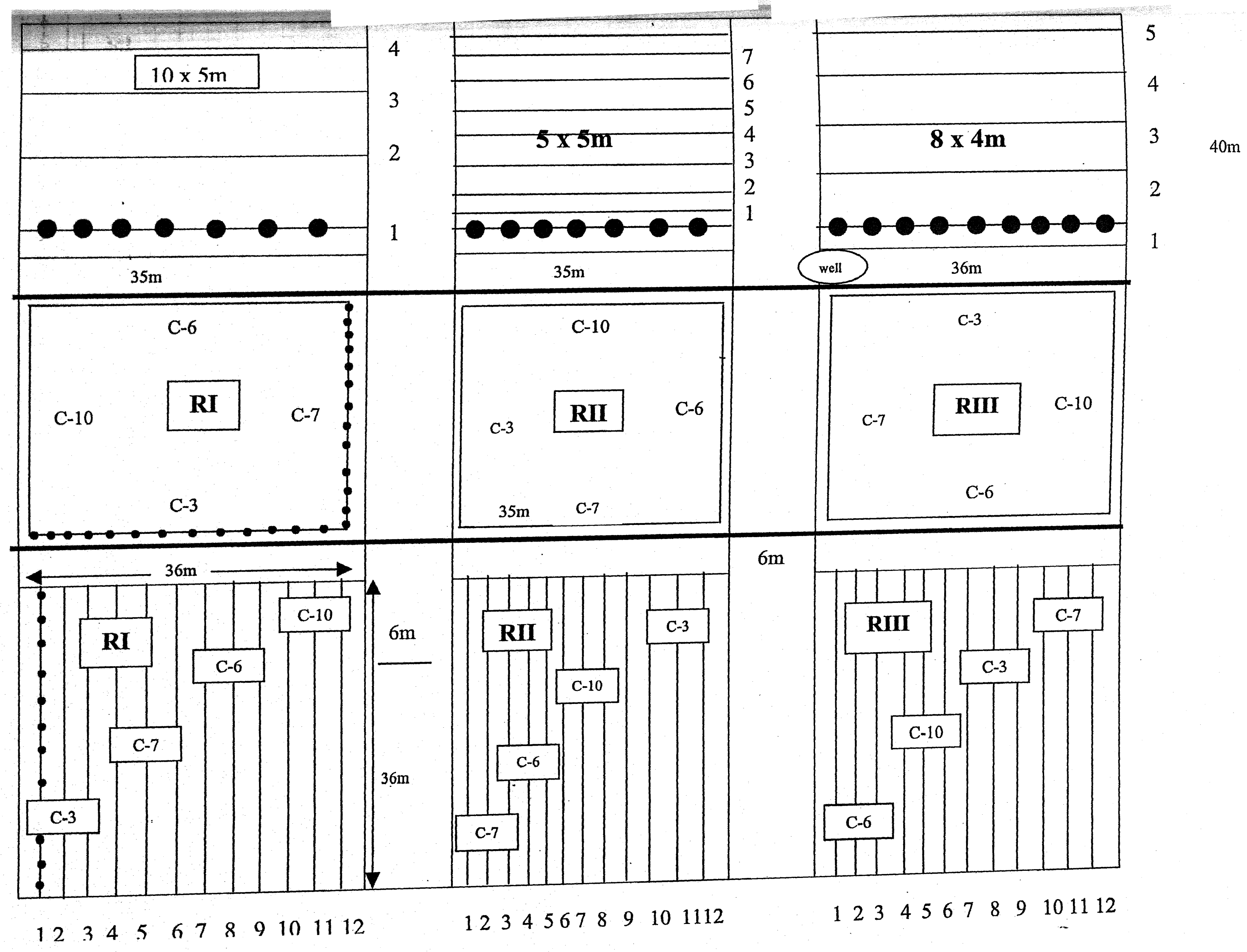
The layout was as below.

Old Eucalyptus Plantations




Block Plantation
Tree spacing 2.5 x 2.5 meter
R II
C-10
C-6
C-7
C-3
C-3
C-7
C-6
C-10
Block Plantation
Tree spacing 2.5 x 2.5 meter
R I
Rows
1 2 3 4 5 6 7 8 9 10 11 12
E.Cameldulendis Var. robust
3
2
EC494241
1
Local
Block Plantation
Tree spacing 2.5 x 2.5 meter
4
C-3
3
C-6
Block Plantation
Tree spacing 3 x 3 meter
2
C-7
1
C-10
WELL
Crop Control


10 x 5m
5 x 5m
8 x 4m
4
3
2
1
7
6
5
4
3
2
1
5
4
3
2
1
40m
35m
35m
36m
well
C-6
C-10
RI
C-7
C-3
C-10
C-3
RII
C-6
35m
C-7
C-3
C-7
RIII
C-10
C-6
36m
6m
6m
36m
RI
C-10
C-6
C-7
C-3
RII
C-3
C-10
C-6
C-7
RIII
C-7
C-3
C-10
C-6
1 2 3 4 5 6 7 8 9 10 11 12
1 2 3 4 5 6 7 8 9 10 11 12
1 2 3 4 5 6 7 8 9 10 11 12



10 x 5m
5 x 5m
8 x 4m
40m
35m
35m
36m
well
RI
RII
RIII
C-3
C-6
C-7
C-10
6m
36m
1 2 3 4 5 6 7 8 9 10 11 12

Chapter-3

Collection and compilation of existing models on Eucalyptus spp. in India and their critical analysis

Collection and compilation of existing models on Eucalyptus spp. in India and their critical analysis.

3.1 Introduction

The estimation of stem volume and tree biomass is needed for both sustainable planning of forest resources and for studies on the energy and nutrient flows in ecosystem. Determination of biomass and growth in vegetation is also an essential component for the estimation of carbon sequestration. Biomass is often estimated using allometry. For scientific purposes standing biomass is a fundamental state variable in several ecological and eco physiological models. Traditionally the determination of aboveground tree biomass has been related to ensure sustainable planning of forest resources. The forester's apply different methods to obtain such estimations. Undoubtedly, the most commonly used mathematical model for biomass studies takes the form of the power function $Y = a*(X)^b$ where 'a' is scaling coefficient and 'b' is the power function, Y is total biomass or volume and X is the Diameter at breast height (D) or total height (H) or D^2H, as the case may be. In most cases, variability of Y is largely explained by the variability of X. The standard method to obtain estimates for the coefficients a and b is by the least square regression of the raw or log-transformed data for X and Y measured from destructive sampling of trees that represents the diameter range within the stand under investigation, This is laborious and time consuming process and it would be difficult to implement it as such at the national level until and unless we make a thorough study of all available equations. Accordingly this work was initiated for an in-depth study at the broader level.

Looking to the complexity of problems for obtaining the data of tree harvesting for different parts of the country, existing equations need to be compiled and evaluated to facilitate identification of the gaps in the coverage of the equations and more, so that the

compiled equations can also be used to test and compare existing equations with new ones, as well as to validate the process based models.

The aim of this study was to develop a database on tree- level stem volume and biomass equations for various eucalyptus tree species growing and researched in India. The whole tree biomass as well as component wise biomass (bole, branch and leaf) was considered for the study. The compiled database is a guide to the original publications of these equations. This database will facilitate effective exploitation of existing information on the growth and yield models of Eucalyptus species in India and the comparison of models on the basis of the equations used *viz,* linear, power, sigmoid, parabolic etc and the cautionary and corrective measures proposed will also be useful in case of growth and yield models for other species in addition to Eucalyptus.

3.2 Data

The development of the presented compilation of equations was based on published equations from different states of India for Eucalyptus plantations. In order to compile the available information, we conducted a literature survey on forestry and forest related journals. We compiled a list of biomass, volume equations for eucalyptus in India, including all the statistical parameters and available information like state, species, measured parameters, unit of parameter, DBH and height range, spacing, age, used equation, equation type, number of trees used for estimating model, etc. During our reference search, we applied no particular selection criteria to exclude certain species or sites, for all cases included in this meta – database.

For all the empirical relationships included in the database, the explanatory variables were always the diameter at breast height (D), the tree height (H) or combination of two, the stem diameter at breast height have been measured at 1.37m above ground (Bruce and Schumacher, 1950[24]. These two variables (D and H) are the most

commonly used independent variables, but equations with several other independent variables like leaf area index, soil, climate, age are not widely developed. Those equations have been considered for description only but were not however included in comparison. The compiled Eucalyptus equations have been presented below according to biomass and volume separately.

3.3 Results

3.3.1 Biomass Equations

We found a total number of 11 biomass equations from different journals covering five species of eucalyptus (*E. tereticornis, E. hybrid, E. globulus, E. grandis* and *E. longama*), for the state of Haryana, Kerala, Tamil Nadu, Uttar Pradesh and Karnataka. Most of the biomass equations were available for aboveground parts of the tree and very few equations were available for the root biomass. In our compilation, we found nine equations for above ground biomass and two for both above ground and below ground biomass. In six equations, variables like DBH, height and biomass were measured but for other five equations D^2H were also measured. For five equations we have find the DBH- range and six equations mentioning spacing of tree plantation, seven equations were allometric, three were linear and one equation was monomolecular. Nine equations mentioned age of trees and for two equations we could not find number of trees used for model estimation. A brief description of these equations is as follows.

Ajit *et al.*, (2006)[6], fitted non linear functions for AGB to the observed data and thoroughly evaluated the model using through residual diagnostic which revealed that the allometric equations: $\text{Biomass}=0.264*(\text{DBH})^{2.173}$ and $\text{Biomass}=0.421*(\text{DBH})^{1.967}$ were statistically valid for a wide range of DBH (1-40) under energy and boundary plantations respectively in semi arid conditions of Uttar Pradesh for estimation of above ground plant biomass.

Tandon *et al.*, (1988)[197], established linear biomass equation for Kerala state at 3, 5, 7, 9 and 11 year old trees of *Eucalyptus grandis*. Regressions were calculated between independent (DBH and height.) variables. Total Biomass= -3.2911 + 0.0207*D^2H produced the best results (and required the least data), which were significant at 1% probability level. The total biomass ranged between 64.797 kg/tree at 3 year age to 300.564 kg/tree at the age of 11 years. Validation of model has not been performed.

Sharma, (1978)[176], developed linear equation for Uttar Pradesh of 8 to 10 year old *Eucalyptus hybrid* and reported the equation as Biomass= -6.10+0.02*(D^2H). A linear equation was also evolved for representing the relation between biomass and volume of tree.

Tandon *et al.*, (1993) [198], fitted many biomass equations for Haryana state in 4, 6, 8 and 10 year old plantation of *Eucalyptus hybrid*. Biomass estimates were made using the stratified tree technique: a total of 17 sample trees were harvested, and measurements were made on above-ground biomass *viz*, stem, bark, leaves, twigs, branches). Various equations were used for the biomass estimates, and those using diameter at breast height as independent variable were selected. The reported equation was Biomass = 0.1353357*$(DBH)^{2.416484}$. Density of the plantations were 1805, 1116, 844 and 955 stems/ha at 4, 6, 8 and 10 years of age, respectively, and total aboveground standing biomass was 20.1, 34.6, 88.7 and 137.7 t/ha, respectively. DBH range was 3.3-20.29 cm. Validation of model has not been performed. Biomass components also increased with age, but while stem biomass increased with increasing diameter and age from 54 to 78%, that of the other biomass components decreased accordingly.

Negi and Sharma, (1987)[132], has reported biomass equation for 6 plantations of *E. globulus* (5-16 year old) and 14 plantations of *Eucalyptus hybrid [E. tereticornis]* (5-20 yr old) in Tamil Nadu. In each plantation, 4-5 sample trees with diameter and height near the average values for each diameter class were felled and values obtained for above-ground biomass. Root biomass for *E. tereticornis* was estimated separately from

data of Uttar Pradesh. Total biomass per ha was calculated by summing the calculated biomass per diameter class. Regression equations were given for relations between D^2H and dry weight. Reported equation was Log (total biomass)= -1.2335+0.09041*Log (D^2H).

Rai, (1984)(a), developed allometric regression equations viz
Log (Biomass)= -0.5181+0.8195*Log (D^2H) and Biomass = -325.69+3.97*(DBH) for Karnataka state. Equations were presented for the relation between biomass of various components of 12 MPTS (*Eucalyptus longana* one of them) and various logarithmic functions of D and D^2H. Log-log relationships gave the best fit. The best estimator of bole biomass was D^2H, and for other components it was D.

Other Biomass Equations

Kushalappa, (1984)[99], presented regression equation $W/D^2 = 0.1139 + 1.562*(1/D^2) + 0.00367*(H/D) + 0.01949*H$ (D-DBH, W-biomass and H- height) for above-ground dry weight, in relation to DBH and total height, based on samples from a 12-year old plantation of *Eucalyptus tereticornis* with spacing 1.2 x 1.2 m for Karnataka state, the DBH range was 2-26cm.

Rai, (1984) (b)[150], developed linear biomass regression equation with respect to variable D^2H for bole, leaf, branch and root biomass separately, no equation was found for total aboveground biomass, the study was conducted for *Eucalyptus Longana*.

Dhawan, (1990)[45], developed correlation between leaf area and leaf dry mass and to leaf number, based on data collected from seedlings of *Eucalyptus hybrid [E. tereticornis]* over the course of a year (starting at the 14-16 leaf stage). The equations were Y = 333.258 +92.277*X and Y = 166.626 + 20.808 which were highly significant (r = 0.99 and 0.98, respectively). A multiple regression equation relating leaf number to leaf area and leaf dry weight was also given.

Dogra,and Upadhyay, (2005)[48], studied for *Eucalyptus hybrid* in Punjab, measured data from 133 permanent experimental plots with age and top heights ranging from 3.9 to 11 years and 6 to 26.2 m respectively and developed various equations that depicted the relation between height and age of tree. Reported equation was Height = 31.5249 – $61.0317/A^{0.7702}$ with $R^2 = 0.47$.

Pal and Raturi, (1991)[136], evaluated the growth parameters and frequency distribution of trees of different categories in an energy plantation of *Eucalyptus hybrid* at the age of three years, and observed that the growth of individual trees in the plantation was very heterogeneous. Variable height was 550-990 cm and girth at breast height (g.b.h.) 5-35 cm. The larger trees (average height 990 cm and g.b.h. 29.0 cm) were much fewer in number (11% of the total) than the medium sized and smaller trees.

It is to be mentioned here that all the equations discussed above are not directly comparable (at a starch in one go) in the sense that they used different dependent and independent variates, varying ages and tree spacings etc. however they can be compared by classifying them on the basis of the type of function used. Accordingly attempts have been made in this study to include maximum possible similar information and details about each published model on biomass and its components (Table-1).
The DBH and height range in the biomass models varied from 2-40 cm and 10-30 m respectively with R^2values greater than 0.95 for majority of models. However for four models moderate values of R^2 were reported ranging from 0.6 to 0.8.

The three models at Sr. No. 1,2 and 5 used power equation of the form $Y=aX^b$ with 'a' values ranging from 0.14 to 0.42 and 'b' values from 1.96 to 2.14. Ter- Mikaelian and Korzukhin, 1997[200] have also reported almost similar 'b' values ranging from 1-3.3 for 65 North American tree species. All these three corresponds to above ground biomass from two states namely Uttar Pradesh and Haryana and both these areas fall

under the semi arid climate accordingly taking the average of the values of 'a' and 'b' parameter may hold good for prediction of AGB under semi arid conditions.

Table-1: Published biomass equations in India at a glance

S. No	Species	State	Variables used	Unit of variables			Observed range	
				Biomass	DBH	Height	DBH	Height
1	*Eucalyptus tereticornis*	Uttar Pradesh	DBH, Biomass	Kg	cm	m	1-40	10-30
2	*Eucalyptus tereticornis*	Uttar Pradesh	DBH, Biomass	Kg	cm	m	1-40	10-30
3	*Eucalyptus tereticornis*	Uttar Pradesh	DBH, Biomass	Kg	cm	m	1-40	10-30
4	*Eucalyptus tereticornis*	Uttar Pradesh	DBH, Biomass	Kg	cm	m	1-40	10-30
5	*Eucalyptus hybrid*	Haryana	DBH, Biomass	Kg	cm	m	3.3-21.0	-
6	*Eucalyptus globulus Eucalyptus Hybrid*	Tamilnadu	DBH, D^2H Biomass	Kg	cm	m	-	-
7	*Eucalyptus globulus Eucalyptus hybrid*	Tamilnadu	DBH, D^2H, Biomass	Kg	cm	m	-	-
8	*Eucalyptus grandis*	Kerela	DBH, D^2H, Biomass	Kg	cm	m	-	-
9	*Eucalyptus hybrid*	Uttar Pradesh	DBH, D^2H, Biomass	Kg	cm	m	-	-
10	*Eucalyptus longana*	Karnataka	DBH, D^2H, Biomass	Kg	cm	m	-	-
11	*Eucalyptus longana*	Karnataka	DBH, Height, Biomass	Kg	cm	m	-	-

Table continued on next page

S. No.	Age (yrs)	Spacing (m)	Equation for	No of trees	Reference
1	11	2 x 2	AG	86	Ajit *et al.*, 2006[6]
2	11	2 x 2	AG	86	Ajit *et al.*, 2006[6]
3	11	3	AG	86	Ajit *et al.*, 2006[6]
4	11	3	AG	86	Ajit *et al.*, 2006[6]
5	4, 6, 8, 10	-	AG	17	Tandon *et al.*, 1993[198]
6	5-16 & 5-20	-	AG+BG	28 & 53	Negi and Sharma, 1987[132]
7	5-16 & 5-20	-	AG	28 & 53	Negi and Sharma, 1987[132]
8	3-11	-	AG+BG	-	Tandon *et al.*, 1988[197]
9	8-10	-	AG	-	Sharma, 1978[176]
10	-	10x10m 2x2m	AG	433(bole) 221(branch) 201(leaf)	Rai, 1984 (a)[149]
11	-	10x10m 2x2m	AG	433(bole) 221(branch) 201(leaf)	Rai, 1984 (a)[149]

AG- Above ground, BG- Below ground

Table continued below

S.No	Equation	Functions	Parameter values		R^2
			a	b	
1	$Y = a^*(DBH)^b$	Allomertic	0.26	2.17	0.70
2	$Y = a^*(DBH)^b$	Allomertic	0.42	1.96	0.82
3	$Y = a + b^*(DBH)$	Linear	-149.08	15.99	0.80
4	$Y = a + b^*(DBH)$	Linear	-376.31	28.05	0.60
5	$Y = a^*(DBH)^b$	Allomertic	0.14	2.41	0.97
6	$Log(Y)=a+b^*Log(D^2H)$	Allometric	1.23	0.09	0.97
7	$Log(Y)=a+b^*Log(D^2H)$	Allometric	-1.04	0.84	0.98
8	$Y= a + b^*(D^2H)$	Linear	-3.29	0.02	0.99
9	$Y= a + b^*(D^2H)$	Linear	-6.12	253.24	0.99
10	$Log(Y)=a+b^*Log(D^2H)$	Allometric	-0.52	0.81	0.99
11	$Y= a+ b^*(DBH)$	Linear	-635.41	55.78	0.95

3.3.2 Volume equations

A total of twenty-six volume equations could be traced from the published literature (Table-2), covering five different Eucalyptus species (*E. Hybrid, E. Globulus, E. Grandis, E. Camendulansis, E. Piularis*) for six states (Tamilnadu, Karnataka, Uttrakhand, Madhya Pradesh, Punjab, and Rajasthan) of India.

In sixteen of the compiled volume equations, the independent variable were diameter at breast height, total height and volume over bark, and six of them use various mathematical combinations of those like D^2 and D^2H. A total of four equation measured volume over bark as well as volume under bark. In seven equations we could not find the DBH and height range. Mostly all the compiled equations for volume were linear, except seven equations those were parabolic and one equation was allometric. Two papers mentioned age of trees and only one paper mentioned spacing. Dogra and Sharma, (2003)[47], does not reported the number of trees used in model estimation. A brief description of these equations is presented below.

Jain *et al.,* (1993a)[80], prepared volume tables (diameter at breast height (D) versus volume over and under bark) and the equations were, $(\text{Volume})_{\text{over bark}} = 0.00183 + 0.00003309{*}D^2H$ and $(\text{Volume})_{\text{under bark}} = -0.121986 + 0.0344338{*}D$ for *E. globulus* in the Nilgiri Hills of Tamil Nadu, based on combined data from eight sample plots in plantations and coppice forests, and using best fit regression equations and furnival index to calculate volume as a function of D^2H and the DBH. The DBH and height range was 6-30 cm and 8-32 m respectively.

Singh *et al.,* (1995)[179], prepared volume tables using data from roadside plantations of *Eucalyptus hybrid [E. tereticornis]* in Uttar Pradesh. Data were collected from 85 trees at 3 x 2m spacing, and different regression models were tried, such as
$(\text{Volume})_{\text{over bark}} = 0.001188 + 0.00003108{*}D^2H$ and

$(\text{Volume})_{\text{under bark}} = -0.090281 + 0.00080164*D^2$. In each model, diameter at breast height (D) was taken in cm, height (H) in meters and total wood volume overbark (VOB) and volume under bark (VUB) in cubic meters. At the age of five years the range of height and diameter was 8-26 m and 9-39 cm respectively.

Jain *et al.*, (1993b)[81], evolved volume tables, for total volume over- and under-bark, together with the regression equations,

$(\text{Volume})_{\text{over bark}} = -0.00458+0.0000361*D^2H$

$(\text{Volume})_{\text{under bark}} = -0.046176+0.00087438*D^2$ containing tree height as a variable, used in their calculation, based on data from 40 trees in Dehradun, Uttranchal state. The observed DBH and height range was 6-30 cm 8-26 m respectively.

Tewari *et al.*, (2001)[205], proposed volume equations for *Eucalyptus camaldulensis* at the Indira Gandhi Nahar Pariyojana Area in Rajasthan. Six different models were fitted to each data set to compute the single and double entry volume equations. Compiled equations for over bark volume with respect to variables D^2H and D were

$\text{Tvob} = -0.00308 + 0.0000333*D^2H$

$\text{Sqrt}(\text{Tvob}) = -0.11887 + 0.031077*D$.

Jain *et al.*, (1991)[79], developed regression equations $(\text{Volume})_{\text{over bark}} = -0.00458 + 0.0000361*D^2H$ and $(\text{Volume})_{\text{under bark}} = -0.046176 + 0.00087438*D^2$ representing the relations between volume and diameter at breast height. The independent variables considered were D^2H and D^2. They also reported that it is often difficult, and even erroneous, to fit a single equation to the whole range of diameters, and in these cases it is advisable to divide the diameter range into small segments and derive a model (equation) for each separately. This technique was applied to diameter and volume data from two types of Eucalyptus plantations in the Punjab: block unirrigated plantations and canal side strip plantations. The 'piecewise' models were shown to give more accurate results than a single model, and based on these, local volume tables were

presented for both plantation types, giving total volumes over and under bark over a 10-40 cm DBH range for both types of plantation.

Pandey and Jain, (1976)[139], presented tables derived from measurements of 233 *E. grandis* trees from plantations of varying density in Kerala and Tamil Nadu, for different age class (6, 8, 10, 12 and 14 years) and developed linear equation of the type $V= a + b^* D^2H + c^* D^2H^*\text{Log } A + d^*H$ for volume, for the DBH range 5-34cm, and height range 6-42m (here A is the basal area).

Surey *et al.,* (1999)[195], developed volume tables for *Eucalyptus Hybrid* for Madhya pradesh by calculating best fit regression equation using data of 993 sample trees. The best fit regression equation was of the form $\text{Log (VOB)} = a + b^*\text{Log(D)}+ c^*\text{Log(H)}$ and $\text{Log(VOB)} = a + b^* D+ c^* (D^2H)+(D^2H)^2$

Dogra and Sharma, (2003)[47], presented linear volume equation with variable D and D^2H separately. Equations were of the form $\text{Log } V=a + b^*\text{Log } D + c^*\text{Log } H$,
$\text{Log } V= a + b^*\text{Log } D$ and $V=a + b^* D^2H$ for *Eucalyptus Hybrid* in Punjab. A total of 111 felled trees ranging in diameter from 7.1cm to 55.7cm and height from 10.0-36.4m at the age of 9-11 years were used for the study.

Chaturvedi and Khanna, (1982)[36], presented linear and parabolic equations of the type $V= -0.0015 + 0.24^*D^2H$ and $\sqrt{V} = -0.084 + 2.5^*DBH$ for *Eucalyptus hybrid*, with D^2H and D as an independent variable.

Tewari and Kumar, (2003a)[201], proposed different volume functions viz $V= -0.00514 + 0.000033^*D^2H$, $V = 0.000169^* D^{2.412}$ for *Eucalyptus camaldulensis* at the Indira Gandhi Nahar Pariyojana Area in Rajasthan, India, and concluded that the combined variable equation performed well in both, the fitting and validation process.

Prasad, (1984)[147], studied on three fertilizer treatments of two varieties of Eucalyptus, 'F.R.I.-4' and 'F.R.I.-5', planted at Gamharia Research Centre (Bihar). The reported equation was $\sqrt{V} = -0.0868 + 2.8335*DBH$.

Other volume equations

Pande and Chaturvedi, (1972)[138], developed correlations between volume over bark, volume under bark with top height, age, mean diameter, top height, on the basis of 284 sample plots from all over India for *Eucalyptus hybrid* and *Eucalyptus tereticornis*.

Chaturvedi, (1973)[35], developed linear regression equations, relating mean annual increment to age, basal area and top height for *Eucalyptus hybrid*. Data were collected from Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, Madhya Pradesh, Maharashtra, Karnataka, Tamilnadu, Andhra Pradesh, Kerala etc. Spacing was varying from 1x1 to 4x4m and age varied from 4 years to 20 years.

Pande, (1974)[137], developed a curvilinear regression equation of stand volume as a function of top height and stem numbers per ha. The equation was $V = -62.453599 + 13.488326*X + 1.972614*X^2$ for 9-12 year old *E. grandis* in Kerala and Tamil Nadu.

Other articles on volume components, but without equations

Choubey *et al.,* (1990)[40], determined the sample size for estimating the volume of Eucalyptus in an agroforestry situation, where diameter, height and volume were measured in 1986 in each of five field boundary plantings of *Eucalyptus hybrid* in Ambala District of Haryana. The plantations were of four types: single sided (1 row along 1 field boundary, 6 yr old); double sided (rows along 2 sides of the field boundary, 6-8 yr old); triple sided (rows along 3 sides of the field boundary, 2 plantations of 6-8 and 12 yr old); and a square plantations (along all 4 sides of the field boundary, 6 yr old). It has been reported that although variability is not uniform for a

given population characteristics from place to place and for varying ages, the coefficient of variation remained fairly stable for population of differing locations and ages.

Singh *et al.*, (1995)[179], prepared volume tables using data from roadside plantations of *Eucalyptus hybrid [E. tereticornis]* in Uttar Pradesh. Single tree data were collected from 85 trees planted at a spacing 3x2m. Different regression models were attempted. In all reported models, diameter at breast height (DBH) is taken in cm, height (H) in meters and total wood volume over bark (VOB) and volume under bark (VUB) in cubic meters. At the age of 5 years, the average height and diameter was 11.1m and 11.4cm respectively.

Prajapati, (1993)[144], reported that a local volume equation of the form V=d*b has been found to be the best fit for a Eucalyptus pole crop (planted in 1983 and felled in 1993) in Dharwad, Karnataka. The coefficient of correlation was 0.9, and the coefficient of determination was 0.8, showing that the 80% variation in volume was explained by the variation in diameter at breast height.

Agnihotri *et al.*, (1989)[2], studied on 20-25 year old *E. alba, E. resinifera, E. tereticornis, E. hybrid [E. tereticornis], E. crebra, E. citriodora, E. melanophloia, E. gomphocephala, E. rostrata* and *E. robusta* for Chandigarh planted at a spacing of 2x2m and reported that the volume was best estimated by a regression equation including basal girth and height as variables, although an equation using diameter at breast height alone was also satisfactory.

Kulkarni and Gore, (1988)[94], studied on a 20 year old *Eucalyptus hybrid [E. tereticornis]* trees in plantation in West Nasik Divsion, Maharashtra, and derived multiple regression equations for volume prediction based on girth, height, girth +

height, and girth + height + girth at 1, 2, 3, 4 and 5 m ht. (g1, g2, g3, g4 and g5 respectively).

As all theses volume equations cannot be compared directly, therefore maximum possible similar information and details of twenty six equations have been compiled in Table-2. The reported DBH range in most of the volume models is 5-30cm where as in few cases it was up to 45cm. The reported height range was 8-32 meters, surprising only in one case it was reported to attain a height of 42 meters. The R^2 values for all the models are extremely satisfactory ranging from 96% to 99% employing thereby that the models are very well fitted over the observed values of harvested data. Equations 1,3,6,9,17,18, and 21 i.e. from Tamil Nadu, Uttar Pradesh, Uttranchal, Rajasthan, Uttrakhand, Uttrakhand, Rajasthan used similar function i.e of the form volume= a+b (D^2H). Interestingly, out of these seven equations, 1,3,6,9, and 21 although developed for different states having varying climatic conditions, different age and spacing) were almost of comparable parameters i.e. 'a' and 'b' values are more or less alike inferring thereby that a common model of volume (over-bark by averaging a and b values) derived out of them may hold good at national level.

However critical comparison of the biomass and volume models can be made on the basis of functional form of the equation developed viz linear, allometric/power, sigmoid, parabolic etc.) Accordingly an analysis of the feasibility, limitations and prediction capabilities of the equation has been made below as per the functional form.

Table-2: Published volume equations in India at a glance

S. No	Species	State	Variables used	Unit of variables			Observed Range	
				Volume	DBH	Ht	DBH	Height
1	*Eucalyptus globulus*	Tamil Nadu	DBH, Height, Volume (OB, UB)	m^3	cm	m	6-30	8-32
2	*Eucalyptus globulus*	Tamil Nadu	DBH, Height, Volume (OB, UB)	m^3	cm	m	6-30	8-32
3	*Eucalyptus hybrid*	Uttar Pradesh	DBH, Height, Volume	m^3	cm	m	9-39	8-26
4	*Eucalyptus hybrid*	Uttar Pradesh	DBH, Height, Volume	m^3	cm	m	9-39	8-26
5	*Eucalyptus hybrid*	Uttar Pradesh	DBH, Height, Volume	m^3	cm	m	9-39	8-26
6	*Eucalyptus camaldulensis*	Uttranchal	DBH, Height, Volume	m^3	cm	m	6-30	8-26
7	*Eucalyptus camaldulensis*	Uttranchal	DBH, Height, Volume	m^3	cm	m	6-30	8-26
8	*Eucalyptus camaldulensis*	Uttranchal	DBH, Height, Volume	m^3	cm	m	6-30	8-26
9	*Eucalyptus camaldulensis*	Rajasthan	DBH, Height, Over bark volume of timber & small wood	m^3	cm	m	-	-
10	*Eucalyptus camaldulensis*	Rajasthan	DBH, Height, Over bark volume of timber & small wood	m^3	cm	m	-	-
11	*Eucalyptus species*	Punjab	DBH, Height, Volume	m^3	cm	m	7-32	-
12	*Eucalyptus grandis*	Kerala, Tamil Nadu	DBH, Height, Volume	m^3	cm	m	5-34	6-42
13	*Eucalyptus pilularis*	Madhya Pradesh	Height, DBH (OB, UB) volume	m^3	cm	m	-	-
14	*Eucalyptus pilularis*	Madhya Pradesh	Height, DBH (OB, UB) volume	m^3	cm	m	-	-
15	*Eucalyptus hybrid*	Punjab	DBH, Height, Volume, D^2H	m^3	cm	m	7.1-43.9	10.0-32.8
16	*Eucalyptus hybrid*	Punjab	DBH, Height, Volume, D^2H	m^3	cm	m	7.1-43.9	10.0-32.8
17	*Eucalyptus hybrid*	Punjab	DBH, Height, Volume, D^2H	m^3	cm	m	7.1-43.9	10.0-32.8
18	*Eucalyptus hybrid*	Uttaranchal	DBH, Height, Volume, D^2H	m^3	cm	m	-	-
19	*Eucalyptus hybrid*	Uttaranchal	DBH, Height, Volume, D^2H	m^3	cm	m	-	-
20	*Eucalyptus species*	Uttaranchal	DBH, Height, Volume	m^3	cm	m	-	-
21	*Eucalyptus camaldulensis*	Rajasthan	DBH, Height, Over bark volume of timber & small wood	m^3	cm	m	5-52	-
22	*Eucalyptus camaldulensis*	Rajasthan	DBH, Height, Over bark volume of timber & small wood	m^3	cm	m	5-52	-

Table continued on next page

23	*Eucalyptus hybrid*	Punjab	DBH, Height, Volume	m^3	cm	m	14-26	-
24	*Eucalyptus hybrid*	Punjab	DBH, Height, Volume	m^3	cm	m	10-16	-
25	*Eucalyptus hybrid*	Punjab	DBH, Height, Volume	m^3	cm	m	10-32	-
26	*Eucalyptus hybrid*	Punjab	DBH, Height, Volume	m^3	cm	m	24-32	-

Table continued below

S. No.	Equation	Type of Equation	a	b	c	d	R^2
1	$(\text{Volume})_{\text{overbark}} = a + b*D^2H$	Linear	0.0018	0.000033	-	-	0.99
2	$(\text{Volume})_{\text{overbark}} = a + b*D$	Linear	-0.1219	0.034433	-	-	0.97
3	$(\text{Volume})_{\text{overbark}} = a + b*D^2H$	Linear	0.0012	0.000031	-	-	0.99
4	$(\text{Volume})_{\text{overbark}} = a + b*D + c*D^2$	Linear	-0.0208	0.006597	0.0009	-	0.96
5	$(\text{Volume})_{\text{overbark}} = a + b*D^2$	Linear	-0.0903	0.000801	-	-	0.96
6	$V = a + b*D^2H$	Linear	-0.0045	0.000036	-	-	0.99
7	$V = a + b*D^2$	Linear	-0.0461	0.000874	-	-	0.97
8	$V = a + b*D + c*D^2H$	Linear	0.0234	-0.009753	0.0011	-	0.98
9	$V = a + b*D^2H$	Linear	-0.0030	0.000033	-	-	0.99
10	$\sqrt{(\text{Twob})} = a + b*D$	Linear	-0.1188	0.031077	-	-	0.98
11	$\sqrt{V} = a + b*\text{DBH}$	Parabolic	-0.1545	0.035370	-	-	0.97
12	$V = a + b*D^2H + c*D^2H*\log A + d*H$	Linear	-0.0377	0.216865	0.0392	0.003	0.97
13	$\text{Log (VOB)} = a + b*\text{Log(DBH)} + c*\text{Log(Height)}$	Linear	0.2000	2.203000	0.000	-	-
14	$\text{Log (VOB)} = a + b*\text{DBH} + c*D^2H + (D^2H)^2$	Linear	0.0018	-0.011086	0.3614	-	-
15	$\text{Log } V = a + b*\text{Log } D + c*\text{Log } H$	Linear	-1.3060	1.921000	1.0160	-	-
16	$\text{Log } V = a + b*\text{Log } D$	Linear	2.6620	2.514000	-	-	-
17	$V = a + b*D^2H$	Linear	0.0405	0.285000	-	-	-
18	$V = a + b*D^2H$	Linear	-0.0015	0.240100	-	-	0.99
19	$\sqrt{V} = a + b*\text{DBH}$	Parabolic	-0.084	2.511	-	-	0.99
20	$\sqrt{V} = a + b*\text{DBH}$	Parabolic	-0.0868	2.8335	-	-	0.99
21	$V = a + b*D^2H$	Linear	-0.00514	0.000033	-	-	.099
22	$V = a * D^b$	Allometric	0.00016	2.412	-	-	0.99
23	$\sqrt{V} = a + b*\text{DBH}$	Parabolic	-0.2297	0.03417	-	-	0.89
24	$\sqrt{V} = a + b*\text{DBH}$	Parabolic	-0.3015	0.04032	-	-	0.90
25	$\sqrt{V} = a + b*\text{DBH}$	Parabolic	-0.2582	0.03606	-	-	0.96
26	$\sqrt{V} = a + b*\text{DBH}$	Parabolic	-0.3670	0.04013	-	-	0.67

Table continued on next page

S. No.	Age(year)	Spacing (m)	Reference	Equation for	No of trees
1	-	-	Jain *et al.*, 1993(a) [80]	Volume	88
2	-	-	Jain *et al.*, 1993(a) [80]	Volume	88
3		3x2	Singh *et al.*, 1995[179]	Volume	85
4	-	3x2	Singh *et al.*, 1995[179]	Volume	85
5	-	3x2	Singh *et al.*, 1995[179]	Volume	85
6	-	-	Jain *et al.*, 1993 (b)[81]	Volume	40
7	-	-	Jain *et al.*, 1993 (b)[81]	Volume	40
8	-	-	Jain *et al.*, 1993 (b)[81]	Volume	40
9	-	-	Tewari *et al.*, 2001[205]	Volume	91
10	-	-	Tewari *et al.*, 2001[205]	Volume	91
11	-	-	Jain *et al.*, 1991[79]	Volume	77
12	4.5-13.5	-	Pande and Jain 1976[139]	Volume	149 & 233
13	-	-	Surey *et al.*, 1999[195]	Volume	993
14	-	-	Surey *et al.*, 1999[195]	Volume	993
15	9, 10, 11	-	Dogra and Sharma, 2003[47]	Volume	81
16	9, 10, 11	-	Dogra and Sharma, 2003 47]	Volume	81
17	9, 10, 11	-	Dogra and Sharma, 2003[47]	Volume	81
18	-	-	Chaturvedi and Khanna, 1982[36]	Volume	-
19	-	-	Chaturvedi and Khanna, 1982[36]	Volume	-
20	-	2x2	Prasad, 1984[147]	Volume	-
21	-	-	Tewari and Kumar, 2003(b)[204]	Volume	91
22	-	-	Tewari and Kumar, 2003(b)[204]	Volume	91
23	-	-	Jain *et al.*, 1991[79]	Volume	77
24	-	-	Jain *et al.*, 1991[79]	Volume	77
25	-	-	Jain *et al.*, 1991[79]	Volume	77
26	-	-	Jain *et al.*, 1991[79]	Volume	77

3.4 Comparison, analysis and critical evaluation of various mathematical functions being used in tree growth modeling

3.4.1 Linear functions

Linear tree growth models employ linear regression to describe the change in the size/ response variate with respect to explanatory variate. The response variate may represent tree volume, biomass etc. and the explanatory variate include age, total height (H), diameter at breast height (DBH), or a combination of these variables says D^2H, to describe the change in response variable (Y) with respect to explanatory variable (X). The use of linear model is very common in forestry/ agroforestry (Chaturvedi and Khanna, 1982[36]; Jain *et al.*, 1993(a & b)[80 &81]; Tewari, 1996[202]; Kumar *et al.*, 1996[96]; Jain *et al.*, 1998[83]; Chaturvedi and Sood, 1995[37]). Basically, these models provide the mathematical building blocks of simple/complex biological growth.

Problem identification and solution

The statistical model employed in linear regression is of the form $Y=a + b*X+ e$, where Y is the response variate, X the explanatory variate, 'a' and 'b' are regression coefficients and 'e' the error term. Statistical procedure to estimate 'a' and 'b' assume that the error term is normally distributed with mean zero, constant variance and independent between cases (Drapper and Smith, 1982[49]). The corresponding mathematical equivalent of simple linear model is the straight line $Y=a + b*X$, where 'a' denotes the intercept on Y-axis, and 'b' the slope of the line ($b=\tan\theta$), where θ is the angle which this line makes with the +ve direction of X-axis). The method of least squares is used to fit this straight line and to estimate the parameters 'a' and 'b' in linear regression using the given data set. There are numerous graphical and statistical methods to support the fitting of the equation and consequently model validation viz the plot of residuals against their expected values; the autocorrelation plot of residuals; the plot of residuals against the estimate; the plot of residuals against the independent variate (Janssen and Titus, 1995[84]; Reynolds *et al.*, 1988[163]; Mayer and Butler,

1993[118]; Soares *et al.,* 1995[187]). All of these are based on the comparison of observed and estimated values and the diagnosis of residuals. Once these statistical assumptions are fulfilled, the linear model may be used for predictive purposes.

However in true sense the biological growth process is not linear, which is the basic assumption in linear models. Due to this reason, simple linear growth models sometimes fail to precisely predict the change in the response variable, particularly for the lower range of explanatory variable. For this range, these models sometimes estimate misleading values and even vague viz-negative values of response variable (Fig. 1). This problem associated with linear tree growth models has been addressed as 'negative estimation' of tree size.

Thus, the linear model reflects a slightly unrealistic picture of tree growth, which is sigmoid in nature. Growth of the tree results from two opposing factors: firstly the positive component associated with biotic potential, photosynthesis activity, absorption of nutrients, constructive metabolism etc. and secondly the negative component representing the restraints imposed by competition, limited resources, stress, respiration and aging factors. These two components when combined together results in the sigmoid shape of tree growth.

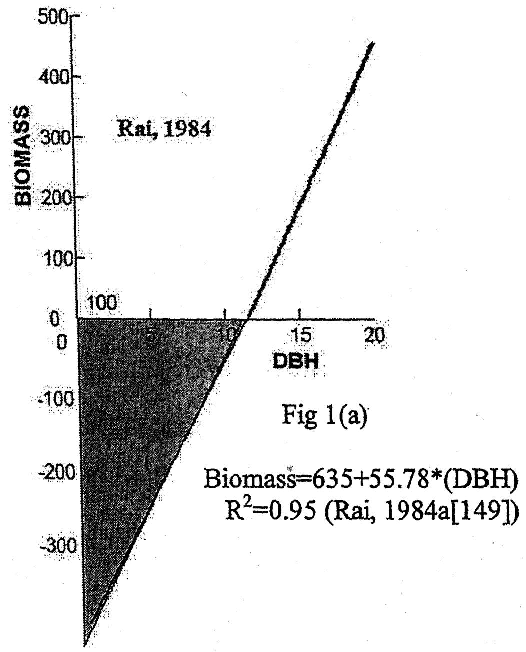
The apparent reason for 'negative estimation of size' with linear models (Singh *et al.,* 1998[178]; Jain *et al.,* 1993(a &b) [80 & 81]; Tokyo *et al.,* 1994[212]; Raj and Cheema, 1990[151]; Jain *et al.,* 1998[83]; Gupta *et al.,* 1996[67]; Jain *et al.,* 1996[82], even with satisfactory R^2 values is that the data set utilized to fit the regression equation represents that range of explanatory variable, belonging to the second phase of growth and which is linear in nature. However, when we use this linear equation for interpolation /extrapolation particularly for lower range the results of prediction are not encouraging and some times vague viz. negative estimation of size. In the last phase (third) they lead to overestimation of size.

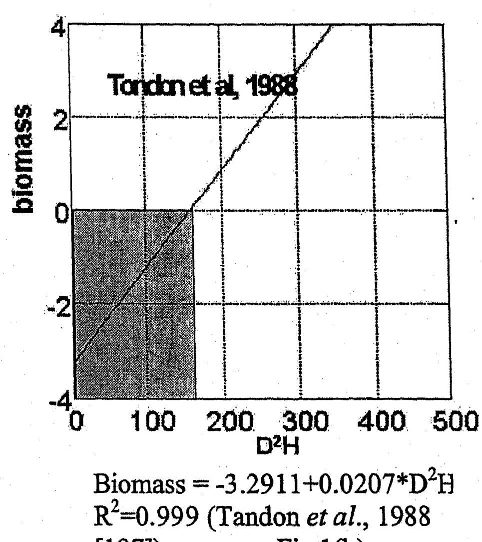
The apparent reason for high R^2 values associated with linear models is that the data set usually belongs to the second phase of tree growth and which is linear in nature. However, reckoning into the prediction capabilities of these models, the results are not encouraging. For the initial (first) phase of tree growth they result in underestimation and even negative estimation and for the last phase (third) they lead to overestimation of size. It is therefore recommended that linear models, in context of tree growth, should be used with caution and in case the fitted simple linear equation results in negative value of 'a' and positive value of 'b', then the lower bound of explanatory variable should be computed as proposed (here viz $X > a/b$) to avoid the negative estimation of tree size (Table-3). Thus when the phenomenon is inherently undesirable, as the negative estimation of size in simple linear models for lower range of explanatory variable, to put implied lower bound on the raw values is most appropriate.

Table-3: Different eucalyptus linear model equations along with the proposed lower bound to avoid the negative estimation problem.

S. No	Model Description	Reference	Lower Bound proposed
1	$AGB = -3.2911 + 0.0207*D^2H$ $R^2=0.99$	Tandon *et al.*, 1988[197]	$D^2H=158.9$
2	$Volume = -6.10877 + 0.253*D^2H$ $R^2=0.99$	Sharma, 1978[176]	$D^2H= 0.024$
3	$(Volume)_{over\ bark} = -0.121986 + 0.0344338*D$ $R^2=0.98$ $(Volume)_{over\ bark} = -0.0083+0.0000309*D^2H$ $R^2=0.99$	Jain *et al.*, 1993(a)[80]	$D=3.54$
4	$(Volume)_{overbark}=-0.090281+0.00080164*D^2$ $R^2=0.96$	Singh *et al.*, 1995[179]	$D^2=112.64$
5	$(Volume)_{overbark}=-0.046176+ 0.00087438*D^2$ $R^2= 0.98$ $(Volume)_{overbark}=-0.00458+ 0.0000361*D^2H$ $R^2=0.99$	Jain *et al.*, 1993(b)[81]	$D^2H=127$ $D^2=52.80$
6	$Twob = -0.00308 + 0.0000333*D^2H$ $R^2=0.99$ $Squa(TWob) = -0.11887 + 0.031077*D$ $R^2=0.99$	Tewari *et al.*,2001[205]	$D^2H=92.49$ $D=3.825$
7	$Biomass = -635.41+55.78*DBH$ $R^2=0.95$	Rai, 1984 (b)[150]	$D = 11.39$
8	$Volume= -0.00514 + 0.000033*D^2H$ $R^2=0.99$	Tewari and Kumar, 2003 (a)[201]	$D^2H = 155.75$

Fig. 1: Function graph depicting problem of negative estimation





Biomass = -3.2911+0.0207*D^2H
R^2=0.999 (Tandon *et al.*, 1988 [197]) Fig 1(b)

3.4.2 Concept of Non Linear function:

Functions other than linear (linear means X to the power one only) may be broadly classified as non-linear models. Non-linear models are in general more powerful than linear ones. The published non-linear Eucalyptus models can be broadly categorized into three main groups, namely allometric, parabolic and sigmoid. Accordingly nonlinear equations has been classified and presented below into three categories.

3.4.2.1 Allometric/Power function

Allometry is used to describe the morphological evaluation of species, and is based on the relation between a tree biomass, volume and of any part of the tree component. The general form of the allometric equation is $Y = a*X^b$ where **y** = measure/process in question viz volume/biomass, X is size (usually DBH), b is the allometric exponent (which tells about the relationship between x & y), and a = a constant (the allometric coefficient). Allometric equation, that compensates for nonlinear functions is: $\log(Y) = \log(a) + b[\log(X)]$. Allometric modeling may be theoretically, physiologically, and statistically superior to alternative methods of modeling used in tree growth estimation.

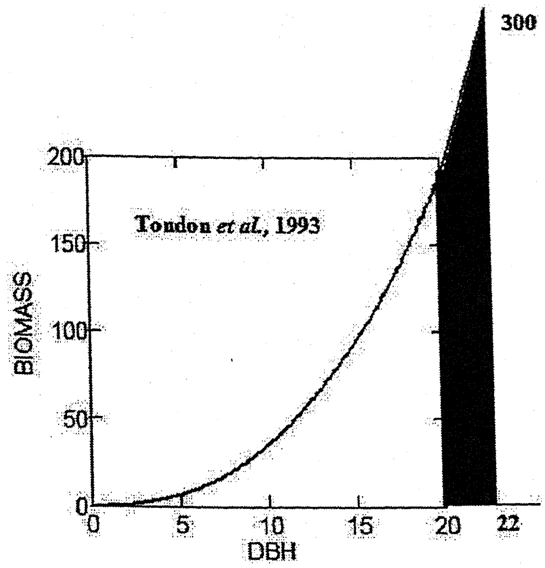
Table-4: Different eucalyptus allometric model equations

S. No.	Model Description	Reference
1	Biomass = $0.1353357*(DBH)^{2.416484}$ $R^2 = 0.97$	Tandon *et al.*, 1993[198]
2	Log (biomass) = $-1.2335+0.09041*\text{Log}(D^2H)$ $R^2=0.98$ Log(biomass)= $-1.0376+0.84*\text{Log}(D^2H)$ $R^2=0.98$	Negi and Sharma, 1987[132]
3	Log(biomass) = $-0.5181+0.8195*\text{Log}(D^2H)$ $R^2=0.99$	Rai, 1984(a) [149]
4	Biomass = $0.264*(DBH)^{2.173}$ $R^2 = 0.71$ Biomass = $0.421*(DBH)^{1.967}$ $R^2 = 0.82$	Ajit *et al.*, 2006 [6]
5	Volume = $0.000169*(DBH)^{2.412}$ $R^2 = 0.99$	Tewari and Kumar, 2003(a) [201]

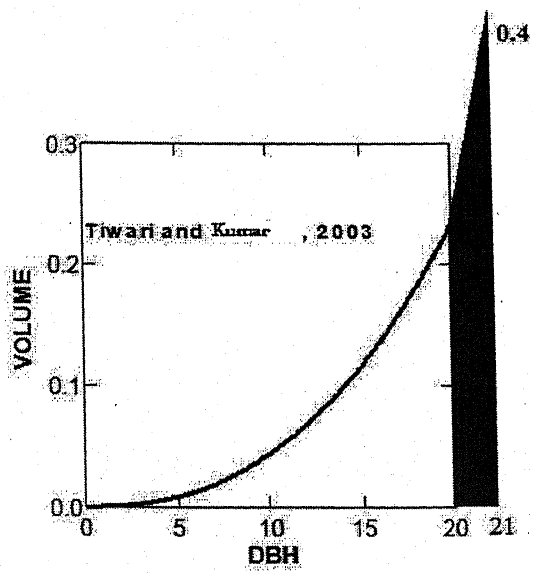
Limitations of allometric models

These allometric equations (Table-4) behave reasonably well within the observed range. However they lead to steep overestimation (Fig. 2) just outside the observed range of independent variable. This overestimation intricacies has been clearly depicted below through the extrapolated graphs of some of the published Eucalyptus allometric models.

Fig. 2: Allometric function graph depicting problem of overestimation



Biomass= $0.1353357*(DBH)^{2.416484}$
$R^2 = 0.99$ (Tandon *et al.*, 1993[198])
Fig 2(a)



Volume= $0.000169*(DBH)^{2.412}$
$R^2 = 0.99$ (Tewari *et al.*, 2003a [201]) Fig 2(b)

3.4.2.2 Sigmoid Function

In forestry/agroforestry studies, growth functions have been used for many years, usually to provide a statistical/mathematical summary or prediction for time-course data on growth of trees. The term growth function is frequently used to denote the rate of change in tree size that may generally be condensed in a single equation. The size may represent the growth attributes of tree viz wood volume, wood biomass, etc. as response variate and age, total height (H), diameter at breast height (D) or a combination of these say D^2H as explanatory variable.

The development of growth functions traces back to 18^{th} century: the prominent and worth mentioning are the equation of exponential decay (Gompertz, 1825[63]) describing the age distribution in human population and Logistic equation (Verhulst, 1838[218]) which are probably the most famous equations in ecology. Though the Gompertz equation was initially developed for population studies, a century later it was applied as a growth model (Winson, 1932[227]). The Gompertz equation was found by Causton and Venus, 1981[32], and many other researchers (Laird *et al.,* 1965[101]; Zweifel and Laskar, 1976[236]; Nokea, 1978[134]; Zullinger *et al.,* 1984[235]) to be more appropriate in biological work than others. An outstanding exposition of Logistic equation is given by Hutchinson (1978)[77]. The early papers of Richards (1959[165], 1969[166]) also contributed to the development of this area and gave a thorough account of growth functions known as Richards functions. The monomolecular equation, also known as the law of diminishing returns in agriculture and economics and law of mass action in chemistry, has not been widely used in forestry. Putter (1920)[148] and Weber (1891)[222] have used this equation in the study of tree growth.

Growth functions, frequently encountered in forestry/agroforestry modeling, may be classified either on the criterion of number of parameters involved (viz two, three or four or higher parameter families) or on the basis of general functional form (viz exponential, hyperbolic, power, monomolecular, etc.). The classical functions like

Logistic, Gompertz, Richards etc. belong to 3-parameter family and the recent developments viz Slodoba, 1971[182]; Zeide, 1992[231], appertains to 4-parameter family. Amongst the exponential form the prominent contributors are Ratkowsky, 1990[156], Huang and Titus, 1992[74], Buford, 1986[25]; Moffat *et al.,* 1991[123], while Tang, 1994[199]; Curtis, 1967[42], etc. augmented the development of hyperbolic class of families.

Majority of the equations described above share a peculiar feature that their growth curves are S-shaped or Sigmoid (Table-5). Recently, various forms of sigmoid functions (simple, reverse, rotated, etc.) have been employed in tree modelling viz stand growth (Feng, 1997)[56], volume growth (Shibuya *et al.,* 1997)[177], survival function (Mason and Whyte, 1997)[117], DBH distribution (Kunisaki and Imada, 1996)[97], fruit development and ripening (Nerd *et al.,* 1998)[133] and disease infection levels (Wiensczyk *et al.,* 1997)[224]. This section discusses the feasibility and limitations of the S-shape growth functions and their suitability in prediction of tree size. The apparent flaw of sigmoid functions has been primarily addressed to as 'Constant Estimation' of size. However, one of the possible solutions to overcome the 'constant estimation' intricacy is to use the concept of simulation to generate the data outside the observed range and then fitting the sigmoid function to the generated data.

While fitting the sigmoid growth models to the data (Table-6), we may sometimes encounter the problem of 'constant estimation of tree size' (Fig. 3) depending upon the observed range of explanatory variate. Smaller the observed range of explanatory variate, greater is the severity of problem i.e. more is the error of prediction in extrapolated zone. The term 'constant estimation of size' means that when we use the fitted sigmoid models for extrapolation, particularly for higher range of explanatory variable, the predicted values of the response variable comes out to be almost uniform. In other words, as the value of explanatory variable increases, the value of the predicted response increases, but the pace of increment is almost negligible and it ultimately leads

to nearly constant estimation of the predicted response. The apparent reason for 'constant estimation' problem is the small observed range of explanatory variate. When the observed range of explanatory variable is large enough, there is no such problem of constant estimation of size with sigmoid functions and due to this reason, for tree growth models with height or DBH as response variate and time as explanatory variate, we may avoid this problem since it is possible to record such data for a long duration. However, for tree yield models which necessitates destructive sampling with timber volume or biomass as response variate and DBH or height as explanatory variate, one would have to wait for years together to harvest trees at different intervals for obtaining a large observed range of explanatory variable in systematically planned experiments for such studies. In usual plantation forestry/agroforestry experiments, the trees are in general more or less of the same age group, and that is why in a single harvesting, there is practically no variability in the observed values of the explanatory variate and which ultimately leads to 'constant estimation' problem while fitting sigmoid functions with such data.

Table-5: Some prominent sigmoid functions with their integral forms

S No.	Reference	General integral functional form	Parameter interpretation
1	Logistic	$Y = a\,(1 + \exp^{(p-b*x)})^{-1}$	a= Asymptote b= Rate of approach to the asymptote p= No direct interpretation
2	Chapman-Richards	$Y = a\,(1-\exp(-b*x))^{1/(1-c)}$	a= Asymptote b= Rate of approach to the asymptote c= Shape parameter
3	Gompertz	$Y = a \exp(-b^{\exp(-q*x)})$	a= Asymptote b= Rate of approach to the asymptote q= No direct interpretation
4	Slodoba	$Y=a \exp[-b.\exp\{-c.x^d\}]$	a= Asymptote b= Rate of approach to the asymptote c= Shape parameter d= No direct interpretation
5	Weibull	$Y=a \exp[1-b.\exp\{-c.x^d\}]$	a= Asymptote b= Rate of approach to the asymptote c= Shape parameter d= No direct interpretation

Table-6: Different eucalyptus sigmoid model equation

S. No.	Model Description	Reference
1	$V= 1605(1-\exp(-0.0073A))^{1.082}$ $PAI = 14.47(\exp(-0.0112A))$	Rayner, 1992[158]
2	$PDIAj = 420[1 - e^{-0.0000420(TDDj - 675)}]^{0.8009}$	Reed *et al.*, 2003[161]
3	$V/B=0.7723+0.3334H -0.0004361HN/B$	Garcia and Ruiz, 2003[58]

PAI = Periodic and mean annual increment

A = Basal area

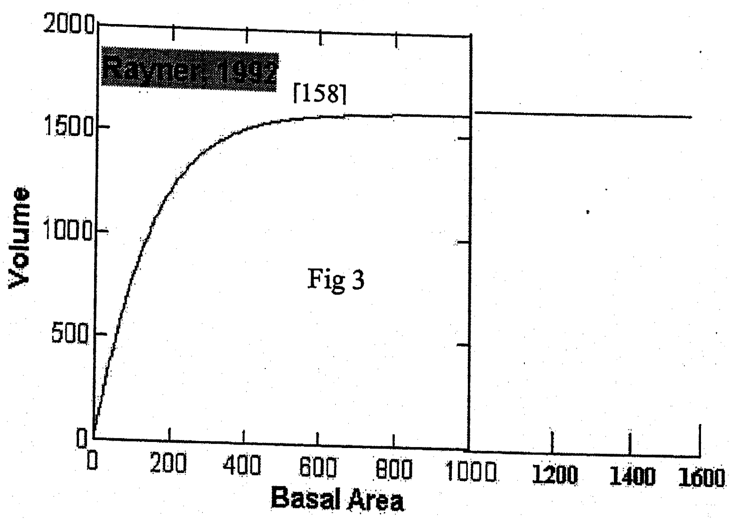
PDIAj = The potential diameter at the j^{th} measurement data

TDDj = The cumulative number of degree days from planting until the j^{th} measured data

V/B = Volume –basal area ratio

H, N and B = State variables (Height, Number of trees and Basal area)

Fig. 3: Function graph depicting problem of constant estimation of size



$$Volume=1605(1-\exp(-0.0073A))^{1.082}$$

Biological interpretation of mathematical function parameters

The sigmoid growth functions have a lot of potentialities that reflect their suitability in tree growth models. To mention a few: most of the parameters of these functions (Table-5) have biological interpretation viz the parameter 'a' represents the asymptotic value of the response variable, 'b' narrates the rate of approach to the asymptote, 'c' is the shape parameter. However, the parameters 'p' and 'q' have as such no direct biological interpretation. Generally, these functions lead to statistically unbiased and efficient models of tree growth.

Advantages

They mimic, the complex tree growth process, more precisely and more accurately and parameters of these models have mathematical description and biological interpretation. They generally lead to statistically unbiased and efficient models.

Disadvantages

These models are not transportable to other data sets for extrapolative predictions since the asymptotic value of predicted size is approximately equal to experimentally observed maximum value of size. For these models theoretically

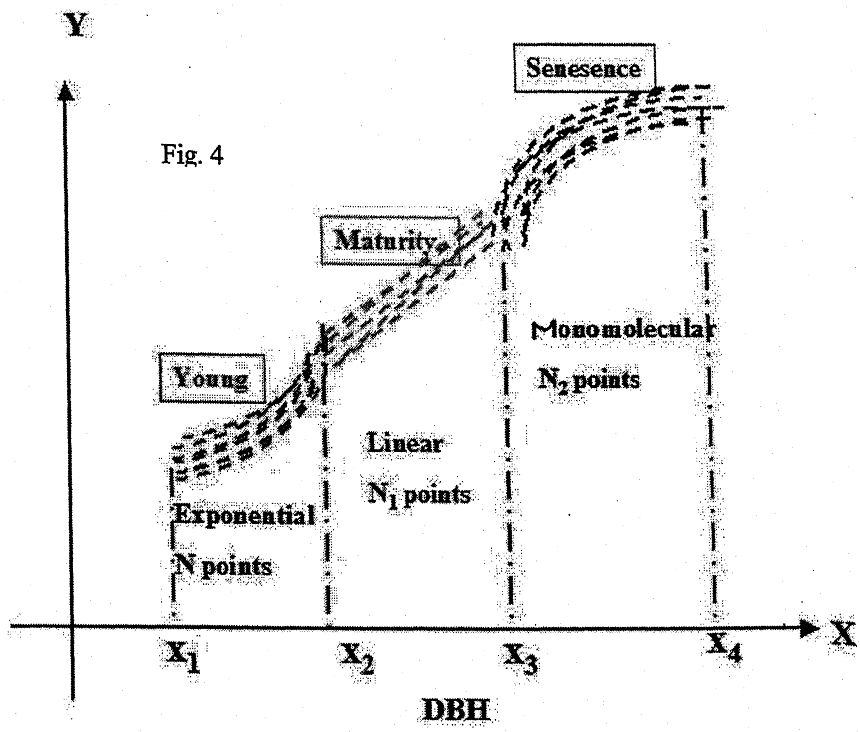
$y \rightarrow C$, the asymptotic value as $x \rightarrow \infty$, but practically $y \rightarrow C$ even slightly outside the actual observed range of x and much before the infinite value of x.

Proposed mathematical/statistical solution to the problem

It is worth mentioning here that linear/curvilinear/allometric models some times may lead to impractical predictions (even negative estimation) for lower range of explanatory variable and sigmoid models result in unrealistic predictions (constant estimation) for higher range. The proposed approach, a combination of curvilinear and sigmoid functions, overcomes the drawback of both the models to a certain extent and results in more realistic predictions for lower and higher ranges. The reason being that the generated data set now includes the feasible 'asymptotic value' of size, which a tree

may attain. Regarding the selection of sigmoid function, the choice may depend on the relative ease of achieving convergence, the equations mathematical properties, and possible biological/physical interpretations of parameters (Fig. 4).

Fig. 4: Graph depicting the mathematical/statistical solution to the problem



Where

N -- Observed data (i.e. the basic observed data set)

$N+N_1$ – Intermediate simulated data

$N + N_1 + N_2$ – Ultimate simulated data

Let (X_1, X_2) represents the observed data range containing 'N' points. Simple linear model is fitted to the observed data range of explanatory variable, and say the resulting

equation is Y= a + b*X, where Y is the response variate/size: X is the explanatory variate: a, b are constants. This developed linear equation is used to simulate/generate additional data points (' N_1' in number) for the DBH ranged by X_1 to X_3. The additional generated `$N_1$' data points are added to the `N' observed data points, thus the intermediate-simulated data set contains ($N + N_1$) point.

Allometric model is fitted to the intermediate-simulated data set consisting of ($N+N_1$), and say the resulting equation is $Y=a*X^b$, where Y is the response variate/size: X is the explanatory variate: a is multiplication constant and 'b' is the shape parameter. The developed allometric equation used to simulate/generate additional data points ('N_2` in number) for the DBH range X_1 to X_4. The generated additional 'N_2' data points are again added to the intermediate-simulated data points, thus the ultimate-simulated data set contains ($N + N_1 + N_2$) points. Suitable sigmoid model is than fitted to the ultimate-simulated data set.

3.4.2.3 Parabolic Equations

A power function with degree two is known as parabolic function. Parabolic function has also been attempted to model volume growth for Eucalyptus species (Table-7). The problem observed with parabolic functions of the type $Y = bX^2$ is again illogical estimation intricacies as shown in the graphical representation of the Eucalyptus volume equation proposed by Jain *et al.,* 1991[79] (Fig.5). For the initial range, as the DBH increases the biomass/volume first decreases from a certain medium values and then it again increases with increasing DBH. In fact, the positive constant term (+a) and the positive linear term (+cX) result in minimizing/decreasing the estimation error term where as the negative constant term (-a) and the negative linear term (–cX) leads to maximizing/increasing increases the estimation/prediction error. This phenomenon has been clearly depicted in the concerned graphs of parabolic functions (Fig's. 6, 6a, 6b, 6a-1, 6a-2, 6b-1, 6b-2).

Table-7: Different eucalyptus sigmoid model equations

S. No.	Model description	Reference
1	$\sqrt{V} = -0.1545 + 0.035370*DBH$ $V = 0.024 - 0.011*DBH + 0.001238*(DBH)^2$ $R^2 = 0.97$	Jain *et al.*, 1991[79]
2	$\sqrt{V} = -0.0840 + 2.511*DBH$ $V = 0.0070 - 0.4228*(DBH) + 6.31*(DBH)^2$ $R^2 = 0.99$	Chaturvedi and Khanna, 1982[36]
3	$\sqrt{V} = -0.0868 + 2.8335*DBH$ $V = 0.0075 - 0.492*(DBH) + 8.02*(DBH)^2$	Prasad, 1984[147]

Fig. 5: Function graph depicting problem of constant estimation of size

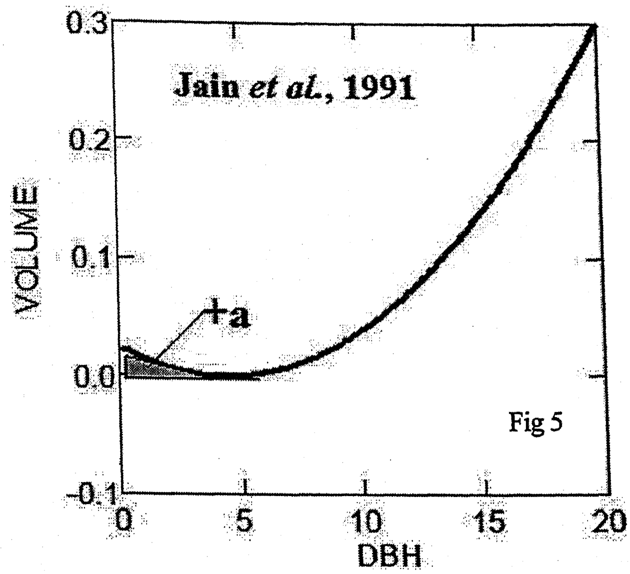


Fig. 6: Equation graph of the basic parabolic function $Y = bX^2$

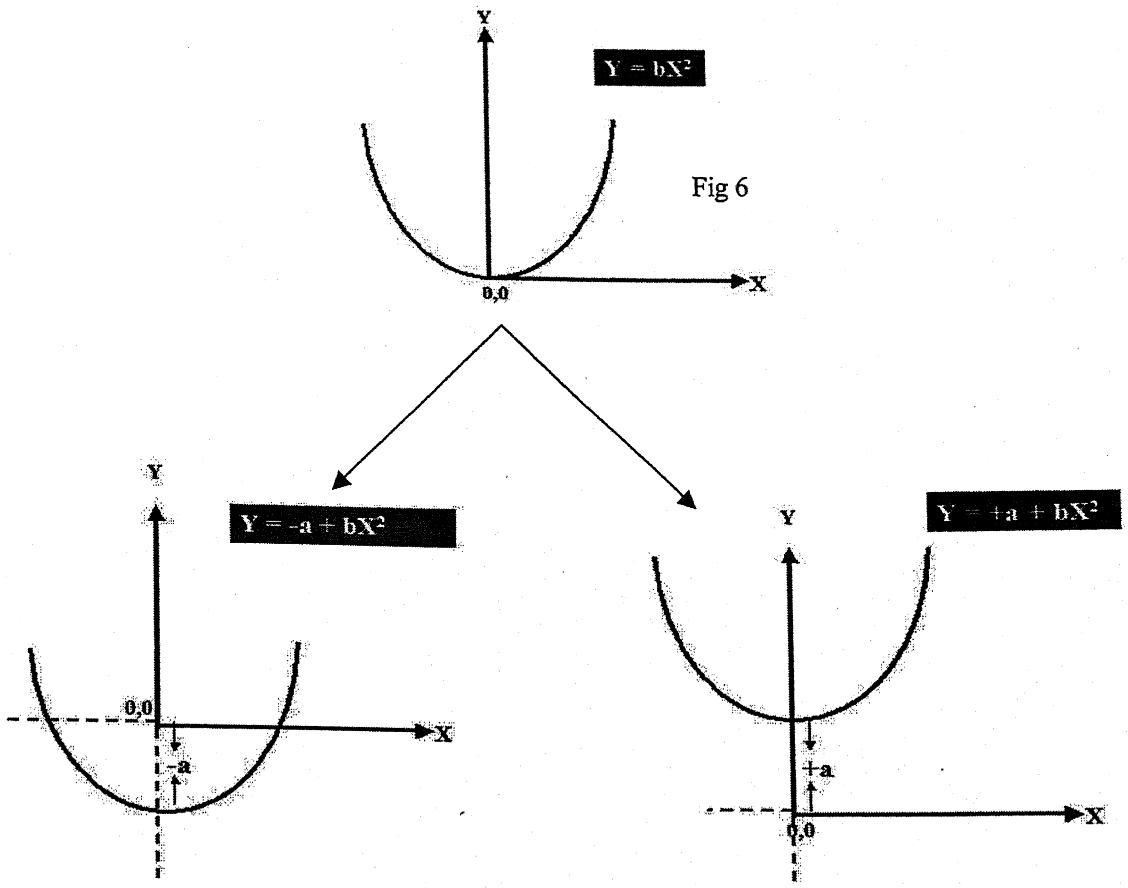


Fig.6a: Effect of inclusion of negative constant term (-a) in the basic parabolic function $Y = bX^2$

Fig.6b: Effect of inclusion of positive constant term (+a) in the basic parabolic function $Y = bX^2$

Fig. 6a: Equation graph of the parabolic function $Y = -a + bX^2$

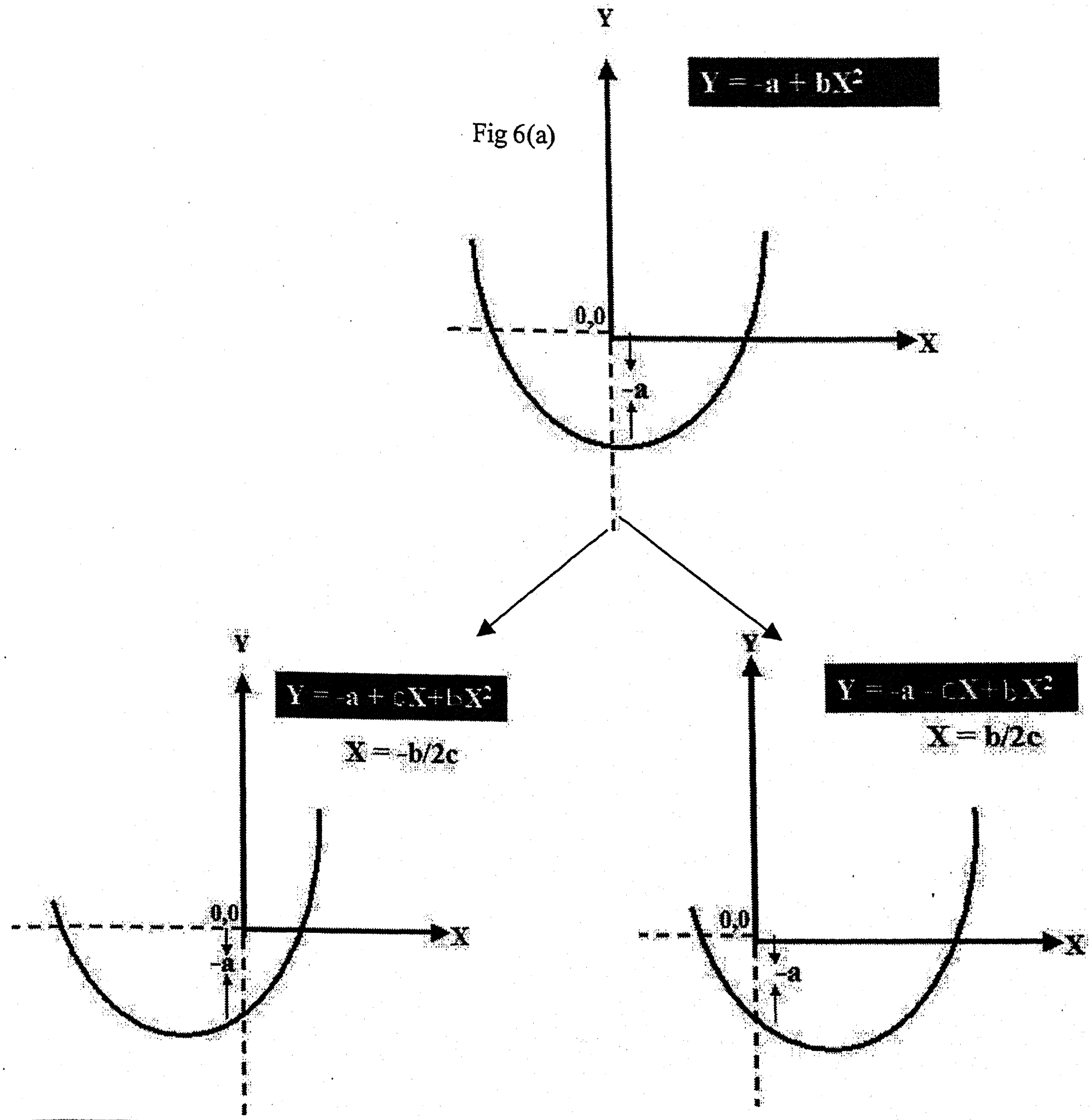


Fig.6a-1: Effect of inclusion of negative linear term (+cx) in the parabolic function $Y = -a + bX^2$

Fig.6a-2: Effect of inclusion of positive linear term (+cx) in the parabolic function $Y = +a + bX^2$

Fig. 6b: Equation graph of the parabolic function $Y = +a + bX^2$

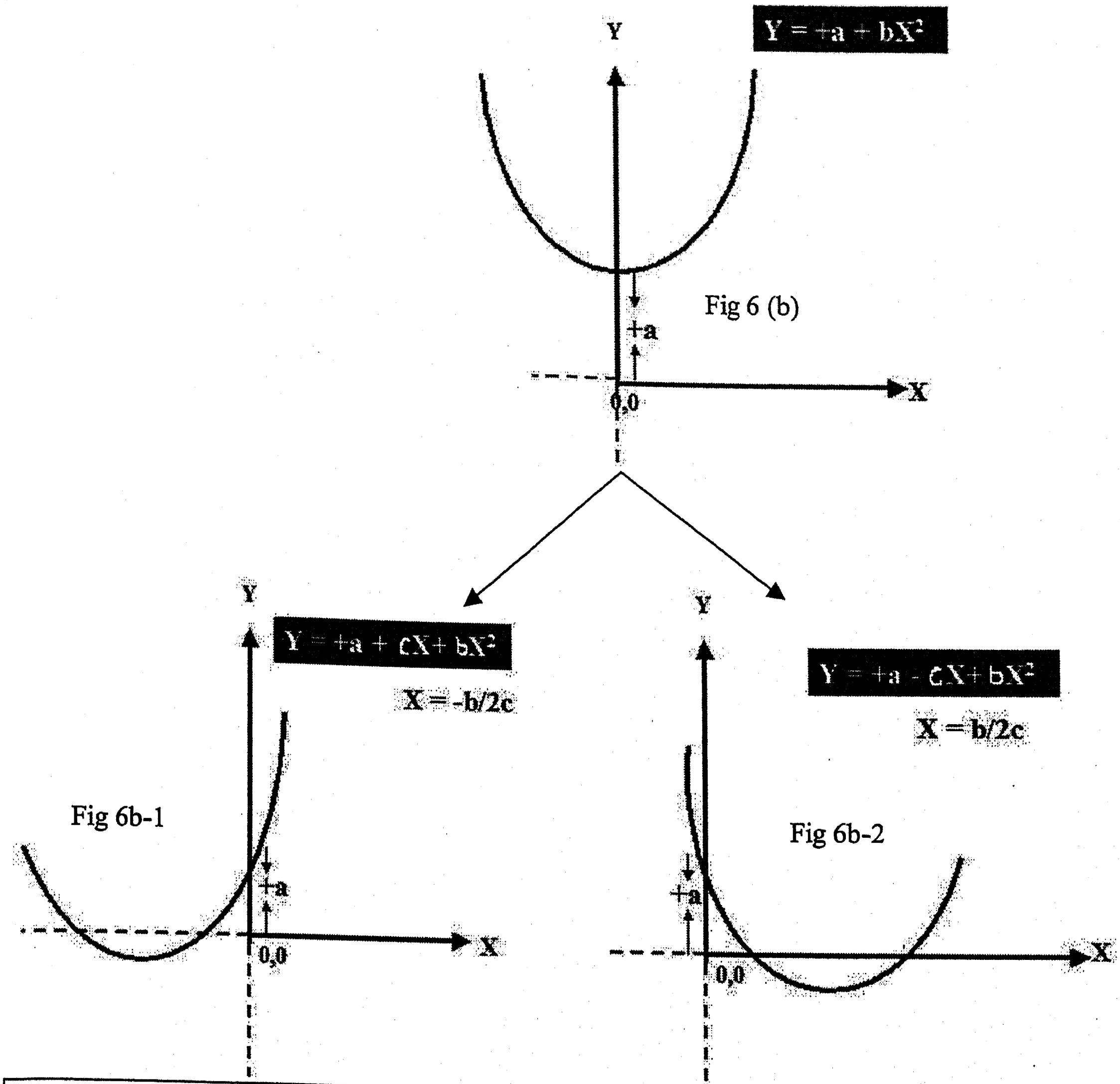


Fig.6b-1: Effect of inclusion of positive linear term (+cx) in the parabolic function $Y = +a + bX^2$

Fig.6b-2: Effect of inclusion of negative linear term (-cx) in the parabolic function $Y = -a + bX^2$

3.5 Comparison of published models using the same type of equations

In this section, we have attempted to have a comparison of similar models. In fact the comparison is that of the model parameters for example if the equation is of the type Biomass = a*(DBH) ^{b} then the parameter 'a' and 'b' are to be compared for different published model. Initially a table of parameters is prepared (Table-8), then these equations are plotted in a single frame (Fig.8a) and finally we have fitted a model (Fig. 8b) in between the two parameters 'a' and 'b' to find out how the value of these two parameters are interrelated. The schematic representation of the comparison made (in the following section) is shown in Fig. 7.

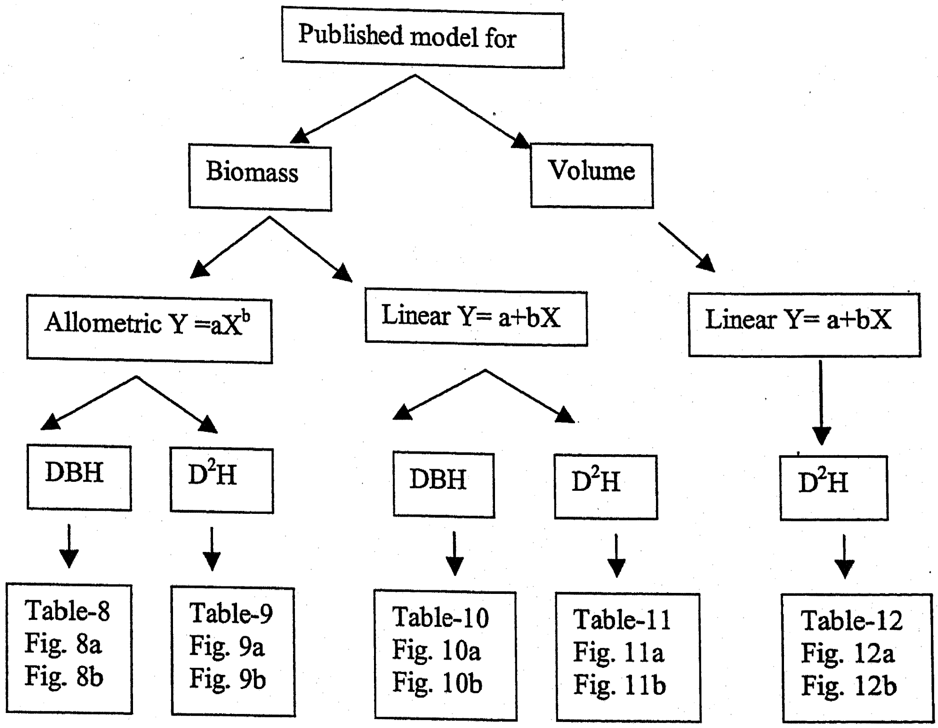


Fig. 7

3.5.1 Comparison of Biomass models (using same type of equation)

In this section, we have compared biomass models. From the published literature, two types of models for biomass could be traces (i) Allometric (ii) linear. Moreover, some of the reported models were based on DBH and others on D^2H. Accordingly, they have been presented below by specifying the type (allometric or linear) and variable used for prediction (DBH or D^2H).

Table-8: Allometric equation Y = a*(DBH) ^{b} for total above ground biomass vs. DBH (parameter comparison)

S. No.	Reference	Parameters		R^2
		a	b	
1	Tandon *et al.*,1988[197]	0.135	2.42	0.971
2	Ajit *et al.*, 2006, (EP)[6]	0.264	2.17	0.82
3	Ajit *et al.*, 2006, (BP)[6]	0.421	1.97	0.70
4	Ritu, 2006 (AS)[167]	0.227	2.15	0.99
5	Ritu, 2006 (CB)[167]	0.265	2.08	0.97

Fig.8a: Pictorial view of above ground biomass allometric equations vs. DBH (plotting in a single frame)

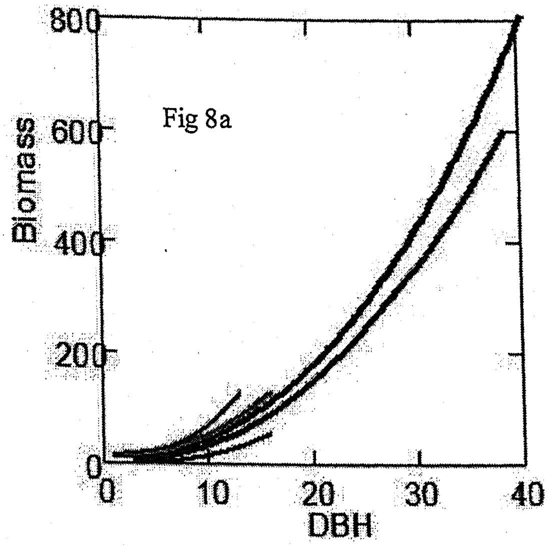


Fig. 8b: Relationship between the parameters of allometric above ground biomass equations vs. DBH (fitting of model between the parameters 'a' and 'b')

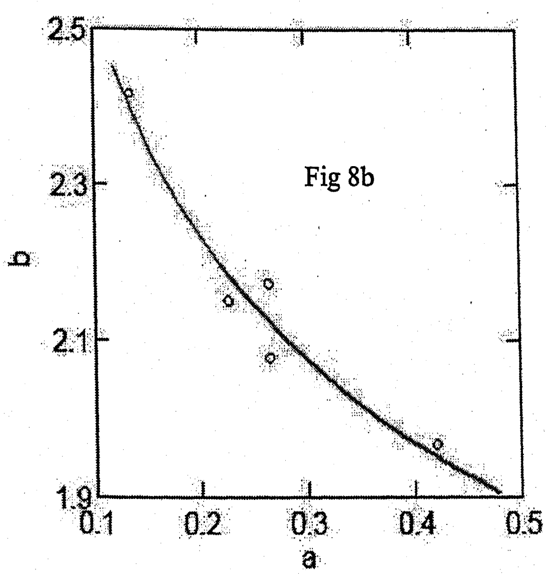


Table-9: Allometric equation $Y = a*(D^2H)^b$ for total above ground biomass vs D^2H (Parameter comparison)

S. No	Reference	Parameters		R^2
		a	b	
1	Ajit *et al.*, 2006, (EP)[6]	0.03	0.94	0.79
2	Ajit *et al.*, 2006, (BP)[6]	0.01	1.08	0.71
3	Ritu, 2006 (AS)[167]	0.102	0.82	0.99
4	Ritu, 2006 (CB)[167]	0.226	0.71	0.96
5	Negi and Sharma, 1987[132]	0.091	0.84	0.98
6	Rai, 1984(a)[149]	0.303	0.82	0.99

Fig. 9a: Pictorial view of above ground biomass allometric equations vs D^2H (plotting in a single frame)

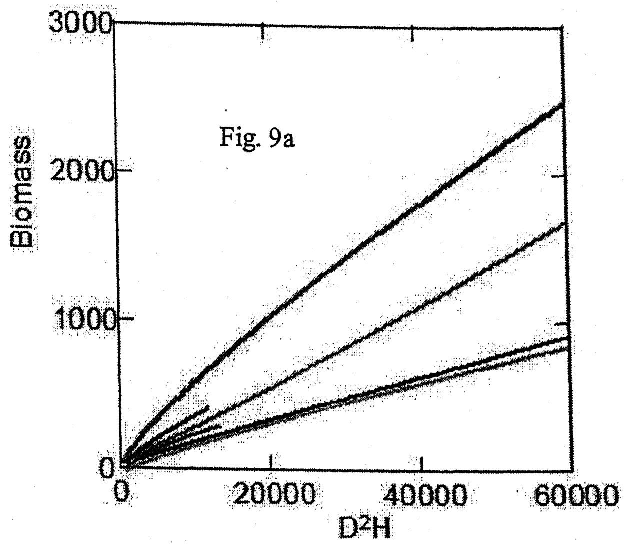


Fig. 9b: Relationship between the parameters of allometric above ground biomass equations vs. DBH (fitting of model between the parameters 'a' and 'b')

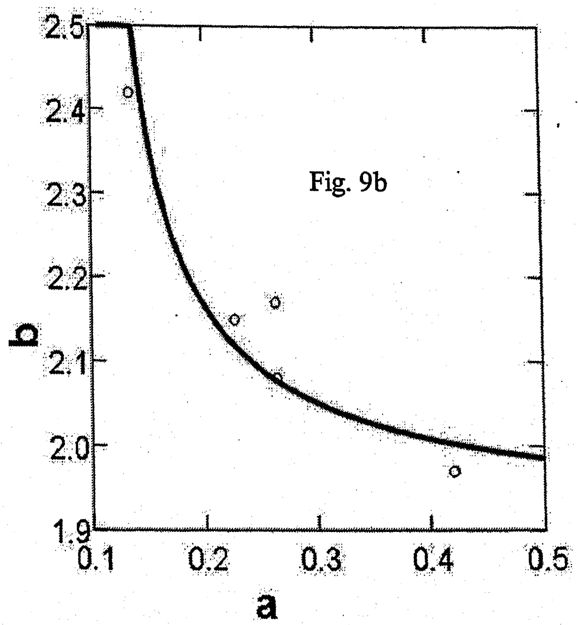


Table-10: Linear equation Y = a + b*(DBH) for total above ground biomass vs DBH (parameter comparison)

S. No	Reference	Parameters		R^2
		a	b	
1	Ajit *et al.*, 2006 (EP)[6]	-149.08	15.99	0.79
2	Ajit *et al.*, 2006 (BP)[6]	-376.31	28.05	0.71
3	Ritu, 2006 (AS)[167]	-9.815	4.132	0.91
4	Ritu, 2006(CB)[167]	-6.025	3.178	0.93
5	Rai, 1984 (a)[167]	-635.41	55.78	0.95

Fig. 10a: Pictorial view of above ground biomass linear equations vs. DBH (plotting in a single frame)

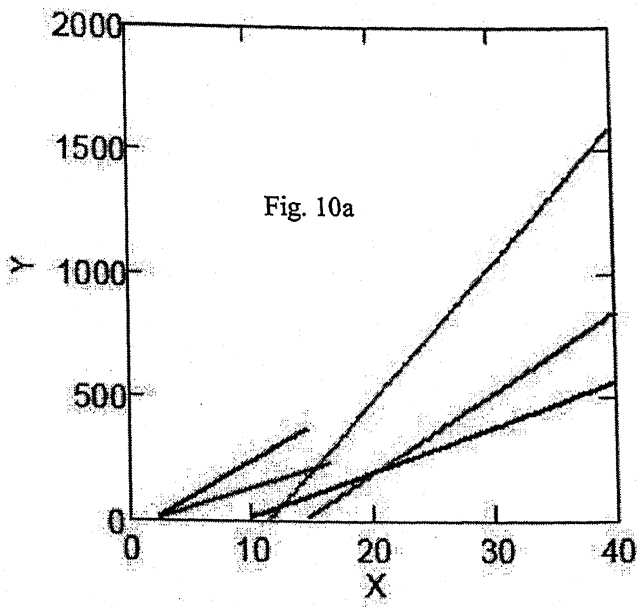


Fig. 10b: Relationship between the parameters of linear above ground equations vs. DBH (fitting of model between the parameters 'a' and 'b')

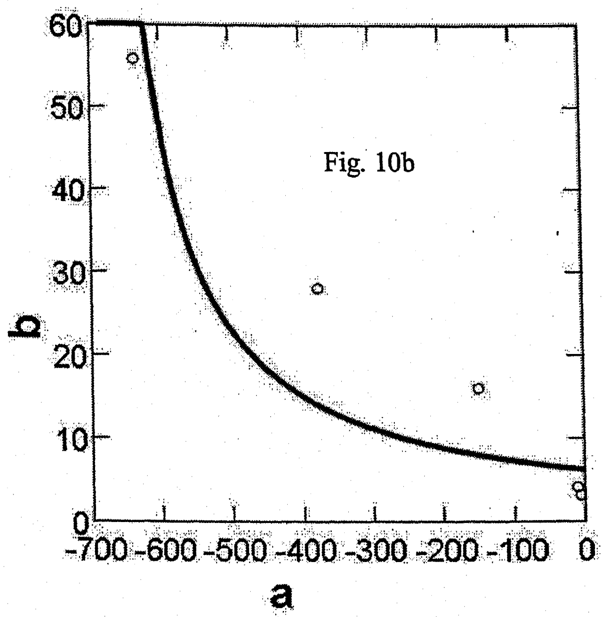


Table-11: Linear equation $Y = a + b*D^2H$ for above ground biomass vs D^2H (parameter comparison)

S. No.	Reference	Parameters		R^2
		a	b	
1	Sharma, 1978[176]	-6.108	0.0253	0.99
2	Tandon *et al.*, 1993[198]	-1.233	0.090	0.97
3	Ajit *et al.*, 2006, (EP)[6]	7.976	0.02	0.79
4	Ajit *et al.*, 2006, (BP)[6]	-3.272	0.025	0.71
5	Ritu, 2006 (AS)[167]	3.169	0.026	0.93
6	Ritu, 2006 (CB)[167]	0.86	0.03	0.98

Fig. 11a: Pictorial view of above ground biomass linear equations vs D^2H (plotting in a single frame)

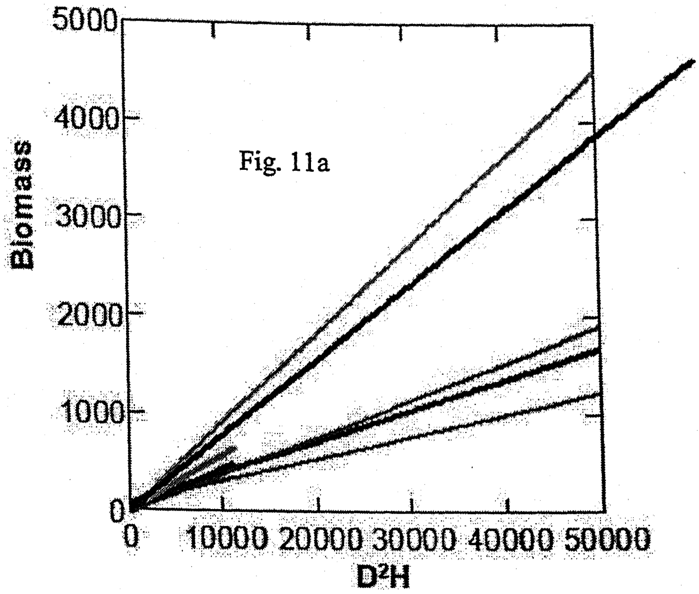
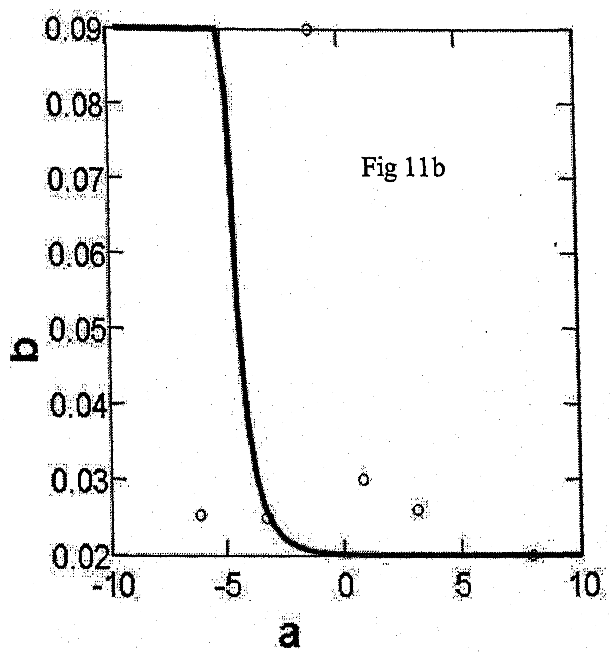


Fig. 11b: Relationship between the parameters of linear above ground equations vs. D^2H (fitting of model between the parameters 'a' and 'b')



3.5.2 Comparison of Volume models (using same type of equation)

In this section, we have compared volume models. From the published literature it is inferred that in majority of cases only linear models are reported for volume predictions. Moreover, these reported models were based on D^2H only, and accordingly they have been covered in a single heading.

While making the comparison of published models using the same types of equations, it was observed that for the power equation ($Y=a*X^b$ there was a clear cut negative correlation between these two parameters i.e. as the value of 'a' increases, the value of 'b' decreases and vice versa. The same trend was observed in biomass Vs DBH (Fig. 8b) and biomass Vs D^2H (Fig. 9b). Almost similar trend was observed for the linear equations models ($Y=a+b*X$) for Biomass Vs DBH (Fig. 10b) and Biomass Vs D^2H (Fig. 11b). The same trend was apparent for the linear models of volume Vs D^2H (Fig. 12b).

Table-12: Linear volume function = a + b*(D^2H) for volume vs. D^2H (parameter comparison)

S. No.	Reference	Parameters		R^2
		a	b	
1	Jain *et al.*, 1993 (a)[80]	0.00183	0.00003309	0.99
2	Singh *et al.*, 1995[179]	0.001188	0.00003108	0.99
3	Jain *et al.*, 1993(b)[81]	-0.00458	0.0000361	0.99
4	Tiwari *et al.*, 2001[205]	-0.00308	0.0000333	0.99
5	Dogra and Sharma, 2003[47]	0.0405	0.0000285	-
6	Ritu, 2006 (AS)[167]	0.0015	0.0000375	0.99
7	Ritu, 2006 (CB)[167]	0.0011	0.0000375	0.97
	Mean	0.005494	0.0000339	

Fig. 12a: Pictorial view of volume linear equations vs. D^2H

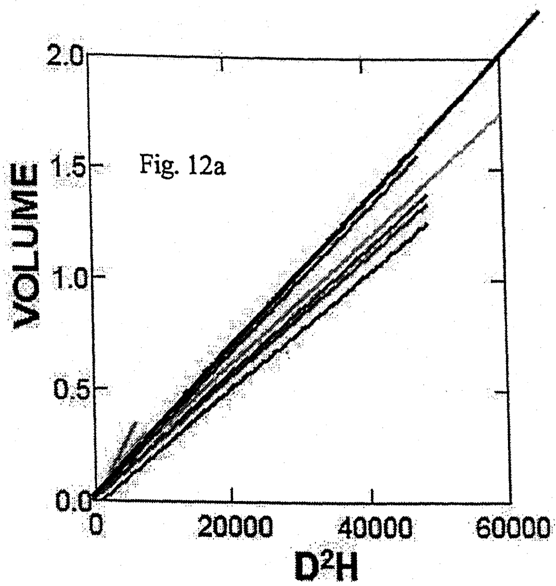
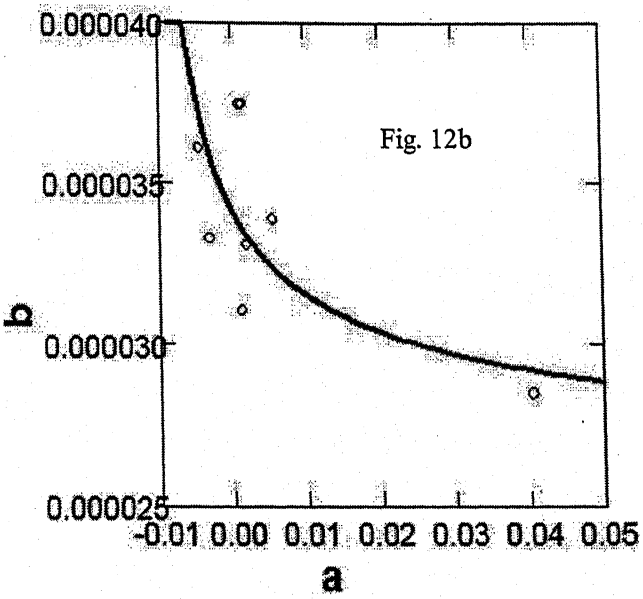


Fig. 12b: Relationship between the parameters of volume linear vs. vs. D^2H (fitting of model between the parameters 'a' and 'b')



3.6 Concluding remarks

The majority of the published equations on biomass and stem volume of Eucalyptus species can be broader classified into four functional types. Linear models, in general suffered from the problem of negative estimation of size (Fig. 1) particularly for the lower range of independent variate. It is therefore advisable to put a lower bound on the value of explanatory variate i.e. the lower limit below which the function should not be used for extrapolative predictions.

The non-linear category of functions (in this case allometric /power, parabolic, sigmoid) usually do not suffer from the negative estimation problems. However they are associated with other kind of estimation intricacies. In particular, the allometric/ power functions leads to extreme over estimation of size, just outside the observed higher range of independent variate (Fig. 3). An amicable solution has been suggested to overcome the problem of constant estimation of size by combining the curvilinear and sigmoid functions after simulation of data in a feasible manner (Fig. 4). This approach of simulation of data after initial stage and then applying suitable sigmoid function for fitting at the second stage will lead to a model that may avoid the negative and constant estimation problems.

The parabolic functions, on the other hand, suffers from illogical estimation problem (Fig. 5) in the sense that for the initial range, as the DBH increases the biomass/ volume first decreases up to a certain medium value and then it again increases with increasing DBH. Accordingly, it is not advisable to use parabolic functions for extrapolative prediction purposes.

Thus looking to the negative, constant, over and illogical estimation intricacies associated with the extrapolative predictions by linear, sigmoid, allometric and parabolic functions respectively, It is recommended that while reporting a specific equation for prediction of tree wise volume and biomass, not only the R^2 value and

residuals diagnostics are important but equally important is the behavior of the proposed model outside the observed range of independent variate to avoid the various types of estimation problems that are otherwise generally overlooked.

Chapter-4

Modelling and comparison of growth attributes (height and dbh) of Eucalyptus tereticornis under different systems, spacing and clones

Modelling and comparison of growth attributes (height and dbh) of *Eucalyptus tereticornis* under different systems, spacing and clones.

4.1 Introduction

In forestry, mathematical equations form the basis of many prediction studies. Output from these equations (height, biomass etc.) based on easily quantifiable metrics such as dbh (1.37cm above ground level) have long been employed by foresters and plant scientists for use in ecological research (Ter-Mikaelian and Korzukhin, 1997[200], Anderson *et al.,* 2006[10], Kajimoto *et al.,* 2006[88], Delphis and Levia, 2008[44]). Such models gain importance as modern scientific management relies heavily on well defined growth and yield functions that can be used to access the status of stands at any point of time. *Eucalyptus tereticornis* being exotic to India, its cultivation has spread to nearly the whole of the Indian subcontinent. Large-scale plantations of *E. tereticornis* were established between 1970 and 1985. Nearly 2% of the cultivable land in northwestern India is planted with *E. tereticornis.* The average productivity of *E. tereticornis* plantations is 10 m^3/ha/year on forestlands and 15-10 m^3/ha/year on farmlands. The average productivity of commercial clones is about 20-25 m^3/ha/year and many farmers have achieved up to 50 m^3/ha/year (Lal, 2007[103]). Infact, for the computation of productivity of such plantations, precise measurements of growth attributes (height and diameter) is essential. It has been noticed during the course of experimentation that it becomes extremely tedious to accurately measure the height of large trees (more than 10 meter), whereas the dbh (diameter at 1.37m height) can be easily measured and accordingly height-diameter models provide a handy tool for prediction of height on the basis of dbh values. Recently height-diameter curves have been frequently developed in forestry studies (Sharma and Parton, 2007[175];

Lootens *et al.*, 2007[111]; Castedo *et al.*, 2006[30]; Reed *et al.*, 2003[161]; Mehtatalo, 2005[121]; Inoue and Yoshida, 2004[78]; Sochacki *et al.*, 2007[188]). Presently, no work has been reported on height-diameter models for *E.tereticornis* in India except a few reports like Tewari *et al.*, (2007)[206], Tewari *et al.*, (2002)[207] and Soarces and Tome, (2002)[185], on modelling of eucalyptus under pure plantations. Although growth performance of *E. tereticornis* has (height, dbh) has been reported by several authors (Lal *et al.*, 2006[105]; Kumar and Bangarwa, 2006[95]; Prajapati *et al.*, 2006[145]; Tandon, *et al.*, 1993[198]; Sundararaju, *et al.*, 1995[194]; Aulokh and Sandhu, 1990[14]), but most of these studies have not considered the role of spacing and systems on growth attributes which is important in agroforestry. In the present study attempt have been made to evaluate the growth performance of four clones of *E. tereticornis* planted at eight spacing in three agroforestry systems and to develop height diameter models separately under three agroforestry systems, for reasonable predictions of height values without destructive sampling.

4.2 Data

4.2.1 Study Site and Experimental details

The experiment was carried out at the Central Research Farm of National Research Centre for Agroforestry, Jhansi which is located at an elevation of 300 m above sea level between 24°11' N latitude and 78°17' E longitude in tropical semi arid climate with mean annual rainfall of 900 mm. More than 75% of the rainfall is received during monsoon season (last week of June to first week of September). Mean maximum temperature ranges from 47.4° C (June) to 23.5° C (December) and mean minimum temperature from 27.2° C (June) to 4.1° C (December). The soil of the experimental area is sandy loam with low organic carbon, nitrogen, phosphorous and

medium to high in potassium. The experiment was initiated in August 2003 with four ITC Bhadrachalam clones, viz C_3, C_6, C_7, C_{10} and laid in three systems of *Eucalyptus tereticornis* namely, agrisilviculture (AS), block plantation (CB) and boundary plantation (BP). Tree spacings considered in agrisilviculture were 5x4 m (1), 10x2 m (2), 10x5 m (3), 8x4 m (4) and 5x5 m (5); compact block are 3x3 m (6) and 2.5x2.5 m (7) and boundary plantation is 2.5 m (8). Wheat and Black gram were grown in the interspaces during 'Rabi' and 'Kharif' seasons respectively under boundary plantations and agrisilviculture systems.

4.2.2 Data and observations

The available data includes the tree wise observations on height in meter taken from the ground level to tip of the shoot of the main bole and dbh (diameter at breast height) in centimeter taken at a height of 1.37m at the main bole) for a period of 52 months. During the first year, observations were recorded four times in a year on 1300 trees distributed over the three agroforestry systems viz agrisilviculture, compact block and boundary plantation. Whereas from second year onwards, observations were recorded twice a year on 862 selected trees distributed proportionally over the three systems.

4.2.3 Model fitting and validation

The complete dataset consisted of the tree wise observation on height (m) and dbh (cm) covering an age span of 6- 52 months. Three such datasets were available, one for each of the three systems. Each of the three datasets (AS, CB, BP) were randomly split into two parts: one to estimate the model parameters (estimation dataset) and the other to validate the performance (validation dataset). This split sample approach used 80% of the original samples for model development while 20 % of the sample was reserved for validation (Carmela *et al.,* 2007[29]). The system wise models,

developed using the estimation dataset, were used to compute the predicted height in the validation dataset. The residuals (predicted height- observed height) were also computed and then tested for their normality and other regression requisites. For model validation, linear regression was fitted between the observed and predicted height of validation dataset (predicted height=a+b* observed height); for the perfect fit model, the standard value of 'a' must be zero and 'b' must be one, along with a perfect unity R^2 value. However, in real experimentations, the value of 'a' should be approaching zero and 'b' should be approaching one.

4.3 Statistical analysis

Systat-12 statistical software (Wilkinson and Coward, 2007[225]) was used for computation of descriptive statistics (mean, standard deviation, skewness, kurtosis, Shaphiro Wilk's statistic for normality testing etc), and fitting of different equations (estimates of model parameters, asymptotic standard error of estimate, confidence interval, R^2 values etc) and plotting of various graphs pertaining to residual diagnostics (probability plot of residuals, auto correlation plots of residuals, plot of residuals against their expected values, plot of residual against independent variate). Different functions, frequently used to model height-dbh curves viz schumacher, chapman-richards and allometric were attempted (Table-1) and choice of the best one was based on validation criterions as well as the prediction behaviour of the function within and outside the observed dbh range.

Table-1: Functional form of various functions used for fitting height-dbh curves

Name of function	Functional form	Parameter interpretation
Allometric	Height = $a*(DBH)^b$	'a' – Scaling parameter 'b' – Power parameters
Richards	$Y=a*[1-\exp(-k*x)]^{(1/1-m)}$	a = Asymptote k = Rate of approach to the asymptote m = Shape parameter
Schumacher	Height=1.37+a*exp(-b/DBH)	a = Asymptote b= Shape parameter

4.4 Results and Discussions

4.4.1 Growth attributes

Growth attributes were statistically at par in different systems and spacings, clonal differences were significant. At the age of 22 months, maximum values of height and dbh were recorded for the clone C-3 in 8x4 spacing and similar trend was observed at 52 months (Table-2). At the age of 22 months, the MAI (mean annual increment) of height was 3.96 m in agrisilviculture, 4.1 m in compact plantation and 3.98 in boundary plantation. But with increase in age at 52 months, there was a decreasing trend in MAI and the value was 3.27 m in agrisilviculture, 3.14 m in case of compact block and 3.62 m for boundary plantation, respectively. Chandra *et al.*, 1998[34] reported average MAI for plant height as 2.21m in high rainfall area (Rudrapur, Nainital); MAl for plant height was less than 3.00 mas reported in many studies from different parts of the country viz, Tandon, *et al.*, 1993[198]; Sundararaju, *et al.*, 1995[194]; Aulokh and Sandhu, 1990[14] and Venkatesh and Sharma, 1977[216]. At the age of 22 months, the MAI of dbh was 3.78cm in agrisilviculture, 3.99 cm in case of compact plantation and 3.86 cm in case of boundary plantation. At the age of 52 months, the MAI of dbh was 3.41 cm in agrisilviculture, while it was 3.22 cm in case of compact block and 3.88 cm for boundary plantation respectively. Mean annual increment for dbh in this trial was quite good when compared to results of other trials conducted at various places (Tandon, *et al.*, 1993[198]; Aulokh and Sandhu, 1990[14]). Chandra *et al.*, 1998[34] reported average MAl of 2.27 cm of best provenance in 25 provenances trial of Eucalyptus species at Rudrapur, Nainital which is high rainfall area. Promising hybrids FRI-4 and FRI-5 had MAl of 1.67 cm at Dehra Dun (Venkatesh and Sharma, 1977[216]). Ajit *et al.*, 2000a [3] reported MAI of 3.22 m yr^{-1} for 3.5 yrs of *Eucalyptus tereticornis* clones obtained from TERI, New Delhi. Annandale (2002)[12] reported MAI of height as 2.5m yr^{-1} for *E. cloeziana* at

4.4 years; 3.3m yr^{-1} for *E. urophylla*; more than > 2m yr^{-1} for *E. cloeziana* and *E. robusta*; 1.7 m yr^{-1} for *E.pellita*; 3.20m yr^{-1} of height and 3.02 cm yr^{-1} for *E. camandulansis* in different locations of north Queens land, Australia. Similarly Jara (1991)[85] reported that MAI of height ranged between 1.67-1.82 m yr^{-1} and MAI of dbh ranged between 1.20-1.72 cm yr^{-1} at the age of 6 years for different provenances of *E. saligna* in Australia; MAI of height as 3.18m yr^{-1} and MAI of dbh as 3.22 cm yr^{-1} at 3 years in Australia has been reported by Henson *et al.,* 2007[73]; MAI of height was 1.04m for *E. marginata* clones in Australia as reported by Stukely *et al.,* 2007[192].

4.4.2 Clone evaluation

The survival of clone C-3, C-7, C-10 was 100% in all the three systems whereas that of C-6 was 72.73% at the age of 52 months. Highly significant differences in growth attributes were observed among the four clones, at all stages of observations, under compact block plantations i.e tree control without crops. However, the clonal differences were not significant (p=0.11) in some cases of intercropped systems specifically the growth attributes were statistically at par at 22 and 52 months age in case of boundary plantation and at wider spacings (10x2, 8x4, 5x5m) in agrisilviculture at 52 months of age (Table-2). Maximum growth was recorded for C-10 and C-3 followed by C-7 and least in C-6 (Fig. 1). In majority of cases the clonal differences were highly significant for growth attributes. Infact the differences were not significant only for intercropped systems. This may be attributed to the fact that in the intercropped systems the tree components indirectly receives the benefits of irrigation, fertilization and intercultural operations meant for crop component and this exerts minimum competition for light, nutrients and moisture, and thus clonal variation is suppressed to a certain limit, whereas the clonal variations exhibits dominance in pure tree treatment (compact block) where there is stiff competition for

growth stimulators viz light, moisture and nutrients. The results obtained from this study indicate that genetic differences exist among clones of *E. tereticornis*. Kumar and Bangarwa, 2006[95] also reported clonal differences for all growth characters for *E. tereticornis* in Haryana. Similarly Rao *et al.*, 2005[155] reported both inter and intra clonal variations among four years clones of *E. tereticornis* in Andhra Pradesh.

4.4.3 Role of spacing

Growth performance was evaluated at eight spacing levels spread over three systems. While comparing the average values of growth attributes (height and dbh) under spacing levels, 8x4 performed better compared to other spacings in agrisilviculture system and interestingly it was clone 3, which performed best at both ages. Like wise, 3x3m spacing lead to better growth attributes, at all ages, as compared to 2.5x2.5 in compact block plantations. At two years age, the mean height was higher in CB (3x3m) because initially trees compete for light and therefore the height grows more than crown and diameter but at the age of 52 months optimum values of height was observed in the intercropped systems viz 8x4 in agrisilviculture, 2.5 spaced in boundary plantations. This may be attributed to the fact that wider spacing, both between row to row and plant to plant, result in better growth due to reduced competition for the want of light, moisture and nutrients. The analysis of growth data over 52 months suggests the superiority 8x4 and 10x5m in agrisilviculture over other spacing in terms of both dbh and height (Fig. 2). Over all, significantly higher tree growth was recorded under wider spacing in all the three systems viz, 8x4 and 10x5m in AS, 3x3 in CB and 2.5 in boundary plantation. Several authors reported better plant growth under wider spacing (Swamy *et al.*, 2007[196] for *Gmelina arborea*; Khan and chaudhry, 2007[91] for *Populus deltoides*; Nasir *et al.*, 2006[130]for *Citrus paradisi*). Nevertheless, the results are at early age of plantations in agroforestry and

compact block suggests need of wider spacing and cultivation inputs for optimum growth.

4.4.4 System Comparison

The growth performance was statistically at par in all the three systems during the initial period upto three years of age, however significant and distinctly higher growth was recorded under the two agroforestry systems (AS, BP) as compared to monocropping system (CB) from the third year onwards (Fig. 3). Gill and Ajit (2004)[60] also reported better growth of trees in agrisilviculture compared to silviculture. Dhyani and Tripathi, (1998)[46] also reported similar results under agrisilvicultural practices in northeast India. Patil *et al.*, 2000[141] reported best height growth of Eucalyptus in agroforestry. This may be attributed to the fact that during cultivation of crops, various inputs like fertilizers, irrigation, given to the crop ,seed bed preparation etc. indirectly boost the growth of tree component also. Chauhan *et al.*, 1997[38] have reported that Eucalyptus growth was improved by the intercrops, which closely relates to the finding of the present investigation.

4.4.5 Development and validation of growth models

The descriptive statistics for various growth attributes pertaining to the complete observed dataset for the age group of 1-4.5 years, have been compiled in Table-3. The dbh (cm) values of trees ranged from 0.20 to 22.61 cm and height from 1.08 to 20.04m. Since no other independent data set was available for validation of the models, the original data set itself was randomly splitted into two mutually exclusive and pseudo independent data sets containing 80% and 20 % observations, used for model estimation and validation respectively. The smaller p-values (<0.05) of the Shaphiro-Wilk's statistic confirms the normality of these dependent variates. To get an idea of the shape of the function to be fitted on the data, a scatter plot of height vs

dbh was initially drawn. It was clear from this scatter plot that the candidate functions usually adopted for modeling height-dbh curves viz richards, schumacher and allometric/power will fit well the observed pooled data set (AS+CB+BP). The plots of these fitted functions along with the observed data points have been compiled in Fig. 4. It is clear from the above computations and the graphs of the fitted functions that the R^2 -values are comparable for all the three functions and was maximum for allometric one. However, as has been pointed out by other researchers also in the recent articles (Ajit *et al.,* 2006[6]; Prajneshu and Chandran, 2005[146]), that R^2 value alone should not be used to judge the best fitting function and it is equally important to consider the validation and more importantly the behavior of the fitted function within and outside the observed range of the independent variate. Accordingly, to judge the prediction capabilities of these functions in the extrapolated region, the function curves for the three-fitted function were drawn (Fig. 5) for a wide range of dbh values. These comparative extrapolated prediction graphs of the three fitted functions suggest that the allometric function results in reasonably acceptable estimations, even quite outside the observed range also, whereas the other two namely richards and schumacher leads to merely constant estimation of size for the extrapolated range. Therefore, the allometric functions, which meets both, the criteria's of high R^2-value and reasonably acceptable extrapolated predictions, was preferred over the other two. Accordingly, allometric models were developed separately under the three agroforestry systems on estimation dataset (Fig. 6). The descriptive statistics for various growth attributes pertaining to both estimation and validation dataset for three agroforestry systems for the age group of 1-4.5 years, have been compiled in Table-4. Parameter estimates of the allometric model (Height=a.$(\text{dbh})^b$) on estimation dataset (80%) under different agroforestry systems has been compiled in Table-5. To judge the prediction capabilities of these functions, the system wise models developed in estimation datasets were used to compute the

predicted height in the validation dataset for each system. All these models were evaluated for their statistical validation through residual diagnostics (Table-6). The error of prediction, termed as residual, is computed as the difference in the observed and predicted values. Theoretically, the residual should be independently and normally distributed with mean zero and constant variance. These assumptions were evaluated through pertinent graphs (Fig. 7,8 and 9). The plots of residuals against the explanatory variate (dbh) ensures that the residuals are not being continuously over or under estimated. The plot of residuals against their expected values clearly portrayed the normality of residuals. The plot of residual against estimate indicated that the residual have constant variance. The auto correlation plot of the residuals ensures that the residuals are not correlated. Thus the proposed allometric equations fulfilled the regression requisites. Validation of the model was also ensured by fitting a linear equation (Predicted Height=a+b* observed height) between observed and predicted height (Fig. 10). Theoretically, for a perfect fit model the value of 'a; and 'b' must be zero and one respectively, along with a perfect unity R^2-value. The value of 'a' approaching to zero and 'b' approaching to one ensures the good ness of the fitted model (Table-7). Moreover, the predicted height values constantly increases with increasing dbh values. The proposed models can be used for predicting the height of standing trees at any stage where height estimation is not possible using instruments, particularly in dense plantations.

4.5 Conclusion

The analysis of growth data over years suggests the superiority of wider spacing in terms growth increments for both dbh and height. Overall performance of clone-10 and clone-3 for all three systems was better then other clones. The growth performance was statistically at par in all the three systems during the initial period upto three years of age, however significant and distinctly higher growth was

recorded under the two agroforestry systems (AS, BP) as compared to monocropping system (CB) from the third year onwards. This may be attributed to the fact that during cultivation of crops, various inputs given to the crop like fertilizers and irrigation, indirectly boost the growth of tree component. In model estimation, all used functions (allometric, richards and schumacher function) based on the criteria of R^2 (obs. vs pred.) values, gave comparable results. However, the allometric function led to the best predictions when these functions were validated on the criteria of extrapolated predictions within and outside the observed range. Allometric models were therefore separately developed for three agroforestry systems (AS, CB, BP). However, since model selection using nonlinear regression is an inherently subjective process, and somewhat data dependent, basing the final evaluation of the model on the validation procedure through pertinent graphs and extrapolated prediction seems to be a viable alternative when the prime objective of modeling exercise is prediction.

Table-2: Growth attributes of the clonal Eucalyptus plantations under different agroforestry systems and spacings.

Age	System	Spacing	Variables	Clone				Mean	p-value
				C6	C3	C10	C7		
22 months	AS	5x4	Dbh	7.01	6.51	6.82	8.22	7.14	0.00000
			Height	7.76	7.59	7.55	8.14	7.76	0.019670
		10x2	Dbh	8.59	7.44	8.28	8.43	8.18	0.000119
			Height	8.71	7.87	8.31	8.48	8.34	0.039424
		8x4	Dbh	7.90	9.55	7.58	7.80	8.21	0.000455
			Height	8.14	8.86	7.28	7.63	7.98	0.000705
		5x5	Dbh	7.37	8.75	7.11	7.90	7.78	0.004457
			Height	8.08	8.55	7.27	7.83	7.93	0.000067
		10x5	Dbh	6.89	5.01	6.36	8.28	6.66	0.000165
			Height	7.80	6.96	6.72	7.91	7.40	0.000018
	CB	3x3	Dbh	8.64	8.23	7.70	8.53	8.28	0.000000
			Height	8.41	8.31	8.05	8.42	8.30	0.000333
		2.5x2.5	Dbh	6.46	7.40	6.65	7.16	6.89	0.000024
			Height	7.95	8.10	7.34	8.02	7.84	0.000001
	BP	2.5	Dbh	7.66	7.80	7.69	7.73	7.72	0.918885
			Height	7.81	8.16	7.86	8.04	7.97	0.110120
52 months	AS	5x4	Dbh	13.22	14.86	14.95	12.45	13.90	0.000260
			Height	13.16	14.39	14.45	12.58	13.66	0.000418
		10x2	Dbh	15.70	16.51	17.38	16.36	16.58	0.027328
			Height	15.06	15.67	16.29	15.61	15.72	0.038648
		8x4	Dbh	16.43	20.70	17.19	17.70	18.18	0.013902
			Height	15.52	18.28	16.15	16.53	16.73	0.038387
		5x5	Dbh	17.51	17.75	17.00	15.44	16.77	0.151145
			Height	16.34	16.63	16.07	14.87	15.87	0.136345
		10x5	Dbh	16.45	12.02	14.73	20.30	15.94	0.000000
			Height	15.63	12.24	14.33	18.28	15.18	0.000000
	CB	3x3	Dbh	13.94	15.19	15.35	15.11	14.88	0.000096
			Height	13.73	14.68	14.81	14.61	14.45	0.000096
		2.5x2.5	Dbh	12.19	13.13	15.16	12.49	13.27	0.000004
			Height	12.38	13.10	14.66	12.60	13.21	0.000004
	BP	2.5	Dbh	17.62	16.75	18.61	17.46	17.49	0.030314
			Height	16.40	15.81	17.04	16.37	16.32	0.056657

Table-3: Summary characteristics of growth attributes for complete dataset.

Measured variable	No. of Cases	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
Height (m)	4667	8.85 (1.08-20.04)	4.72	-0.0447 (0.0358)	-1.376 (0.0716)	0.9297	0.0000
Dbh (cm)	4667	8.26 (0.20-22.61)	5.31	0.0680 (0.0358)	-1.225 (0.0716)	0.9441	0.00000

Table-4: Descriptive statistics of model estimation (80%) and validation (20%) datasets under three agroforestry systems

Number of observations	Measured variable	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	*SW Statistic	SW P-Value
Agrisilviculture (crops +trees within field)							
Estimation dataset							
1908	Height	8.62 (1.08-19.38)	4.69	0.066 (0.056)	-1.344 (0.1120)	0.93427	0.000
	dbh	8.02 (0.29-21.66)	5.33	0.168 (0.056)	-1.204 (0.1120)	0.94110	0.000
Validation dataset							
478	Height	8.95 (1.08-18.48)	4.81	-0.010 (0.111)	-1.32 (0.222)	0.93581	0.000
	dbh	8.35 (0.30-20.70)	5.49	0.130 (0.111)	-1.168 (0.222	0.94376	0.000
Compact Block Plantations (pure tree control)							
Estimation dataset							
1311	Height	8.82 (1.40-17.48)	4.52	-0.199 (0.067)	-1.411 (0.135)	0.910	0.000
	dbh	8.14 (0.20-18.47)	4.94	-0.123 (0.067)	-1.319 (0.135)	0.934	0.000
Validation dataset							
355	Height	9.36 (1.40-16.35)	4.53	-0.354 (0.129)	-0.368 (0.258)	0.898	0.000
	dbh	8.76 (0.23-17.83)	4.97	-0.260 (0.129)	-1.27 (0.258)	0.928	0.000
Boundary Plantation (crops+ trees on field boundaries only)							
Estimation dataset							
494	Height	9.60 (1.40-20.04	5.26	-0.119 (0.109)	-1.475 (0.219)	0.909	0.000
	dbh	9.28 (0.28-22.61)	6.01	-0.0036 (0.109)	-1.368 (0.219)	0.929	0.000
Validation dataset							
121	Height	7.94 (1.43-18.00)	4.90	0.314 (0.219)	-1.270 (0.436)	0.914	0.000
	dbh	7.38 (0.35-20.38)	5.50	0.409 (0.219)	-1.004 (0.436)	0.928	0.00001

*SW- Shaphiro wilk's statistic for normality testing

Table-5: Parameter estimates of the allometric model ($Height=a.(dbh)^b$) on estimation dataset (80%) under different agroforestry systems.

System	Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
				Lower	Upper	
AS	a	1.84	0.013	1.814	1.868	0.98
	b	0.76	0.0029	0.756	0.768	
CB	a	1.80	0.024	1.761	1.855	0.97
	b	0.77	0.0054	0.762	0.783	
BP	a	1.76	0.0271	1.709	1.816	0.98
	b	0.77	0.0058	0.768	0.791	

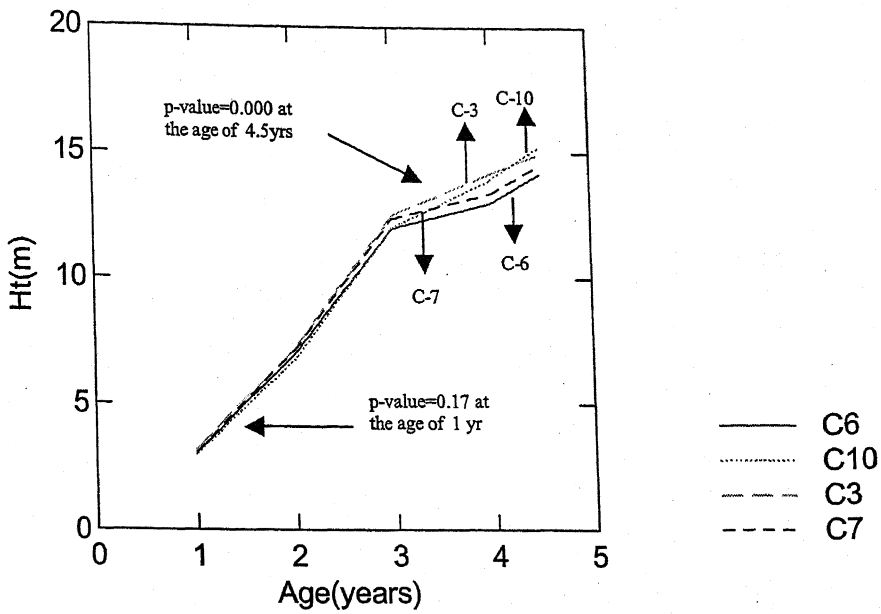
Table-6: Descriptive statistics of residuals computed on validation dataset (20%) under different agroforestry systems.

System	No. of cases	Average	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
AS	478	0.16	0.531	0.496 (0.111)	1.437 (0.222)	0.952	0.000
CB	355	0.14	0.710	1.205 (0.129)	3.142 (0.258)	0.854	0.000
BP	121	0.21	0.614	-0.643 (0.219)	1.116 (0.436)	0.968	0.005

Table-7: Validation of allometric model by fitting a linear equation between predicted and observed height values (predicted height=a+b*observed height) on validation dataset (20%) under different agroforestry systems.

System	Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
				Lower	Upper	
AS	a	-0.14	0.051	-0.24	-0.04	0.98
	b	0.99	0.0050	0.98	1.00	
CB	a	0.09	0.085	-0.070	0.266	0.97
	b	0.97	0.0082	0.957	0.989	
BP	a	-0.01	0.105	-0.22	0.189	0.98
	b	0.97	0.011	0.953	0.998	

Fig. 1: Clone wise comparison of growth attributes over an age sequence.



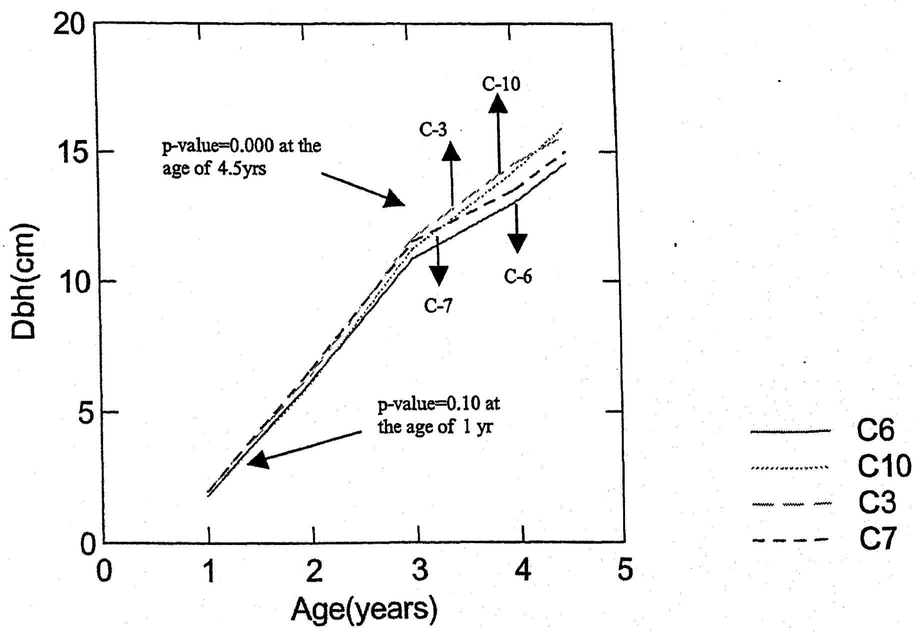
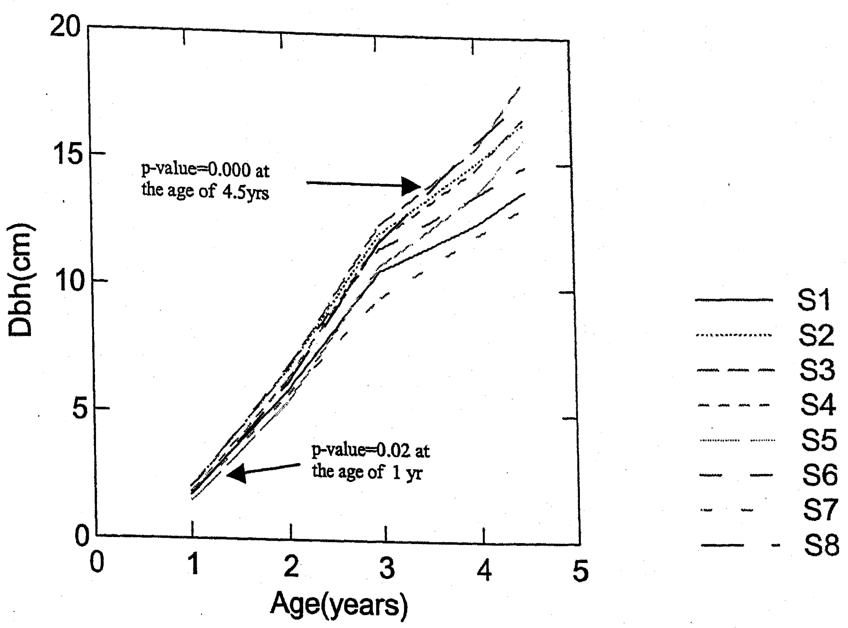
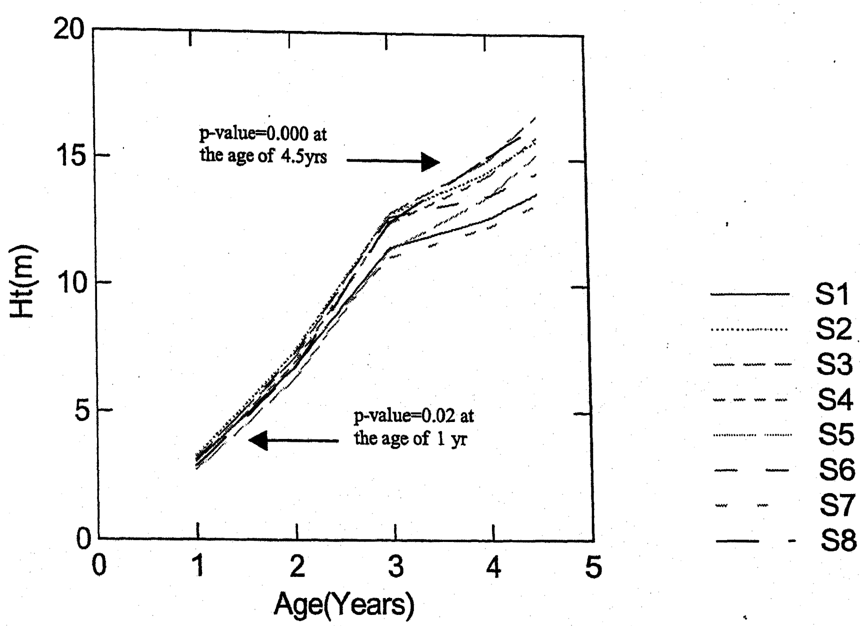


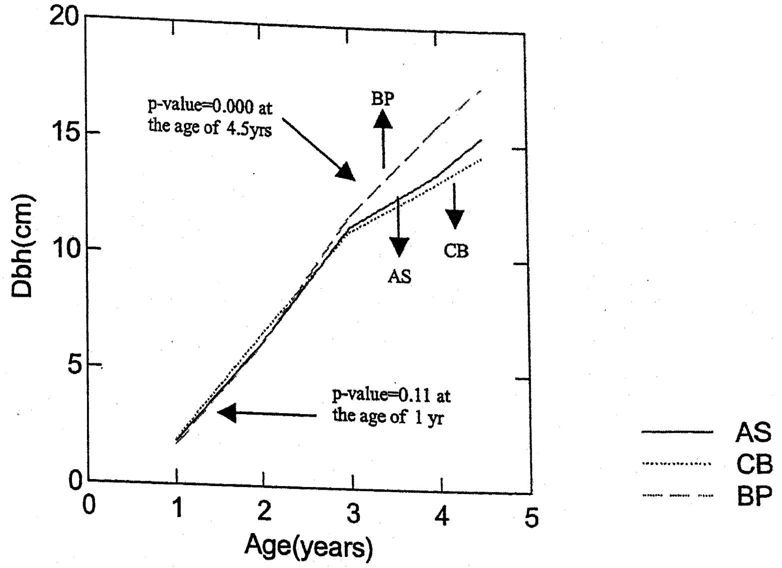
Fig. 2: Spacing wise comparison of growth attributes over an age sequence.





(S_1=5x4m; S_2=10x2m; S_3=10x5; S_4=8x4m; S_5=5x5m; S_6= 3x3m; S_7=2.5x2.5m; S_8=2.5m)

Fig. 3: System wise comparison of growth attributes over an age sequence.



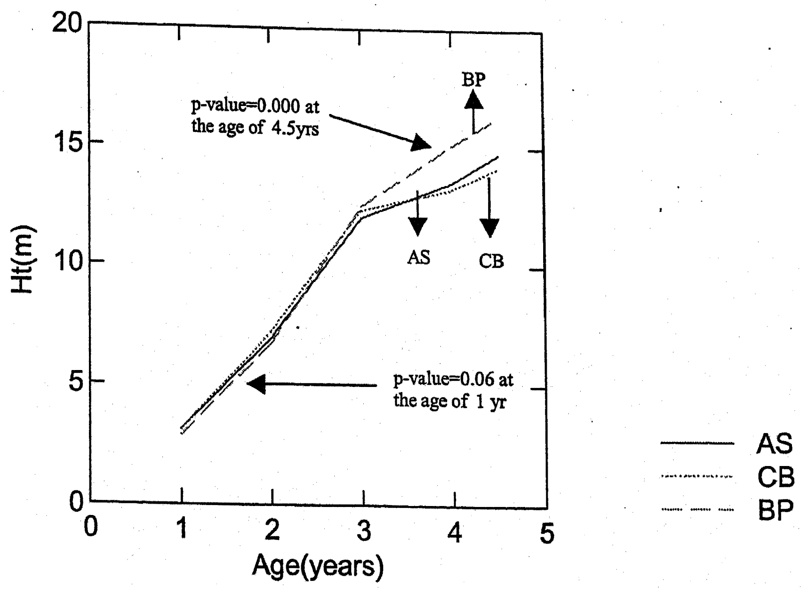


Fig. 4: Different function fitted to model the height-dbh relationship on the pooled dataset (AS+BP+CB) along with the observed points.

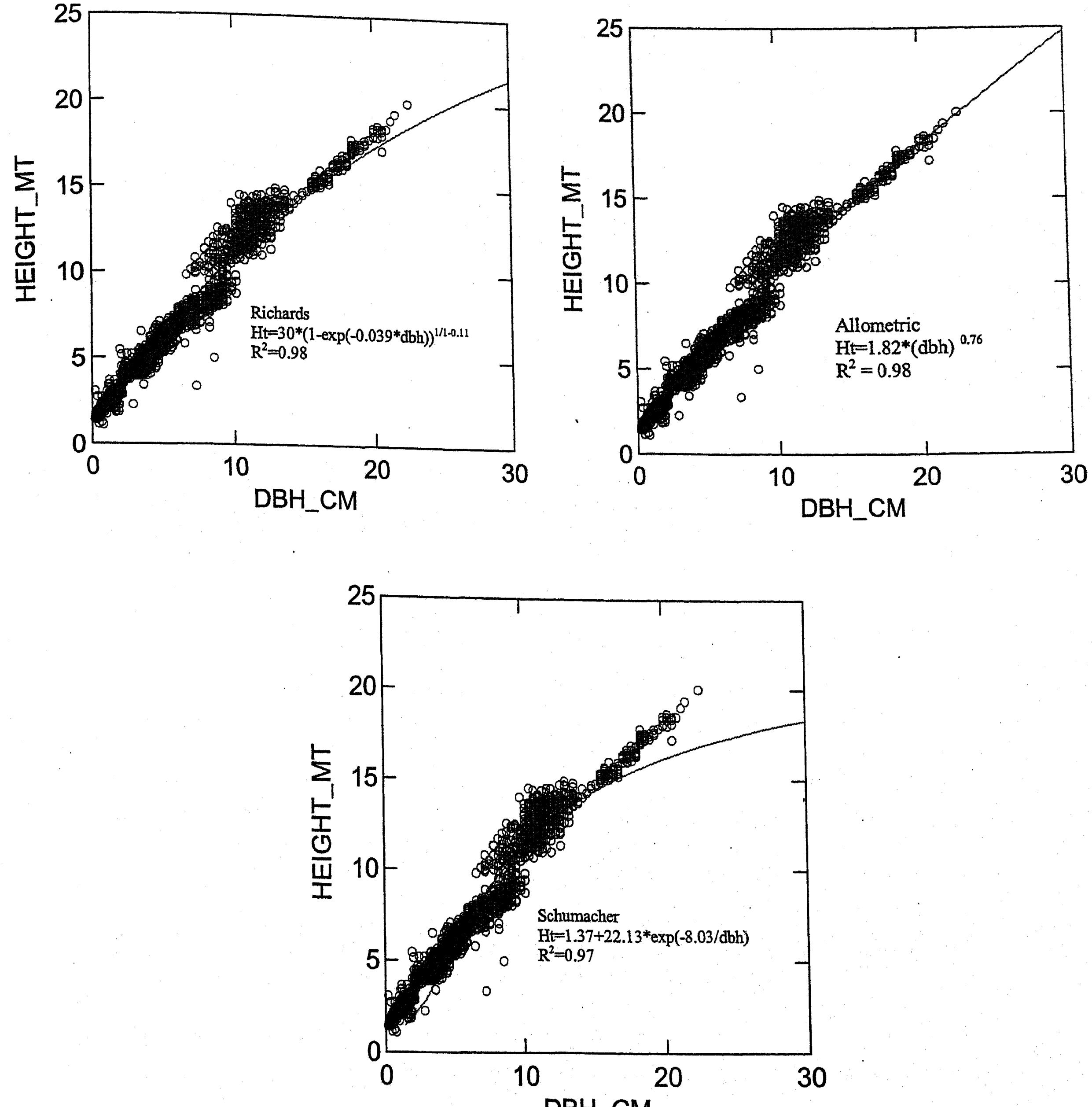


Fig. 5: Extrapolated predictions of growth with different functions fitted on pooled dataset.

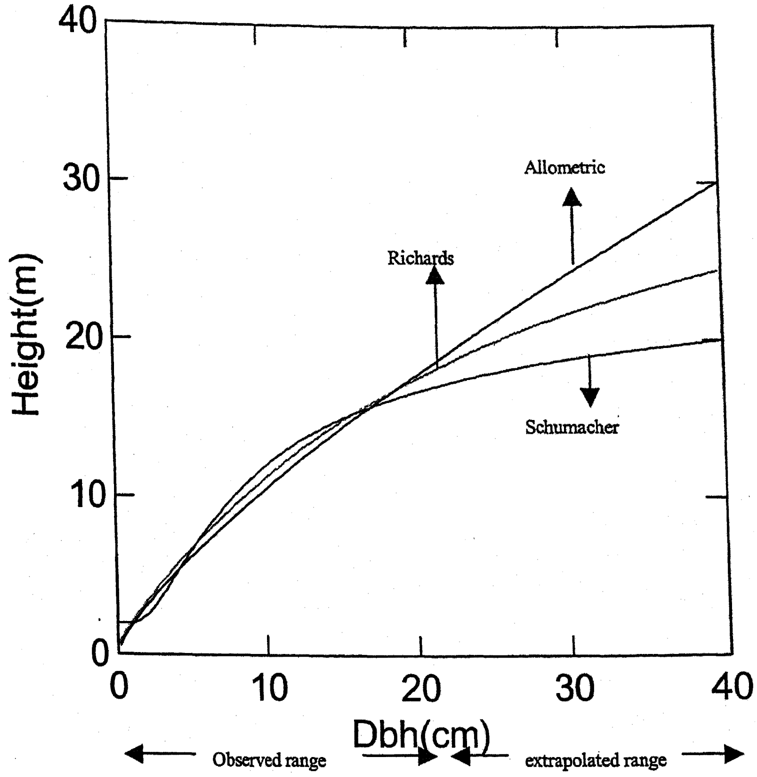


Fig. 6: Allometric function fitted on individual datasets under the three agroforestry systems.

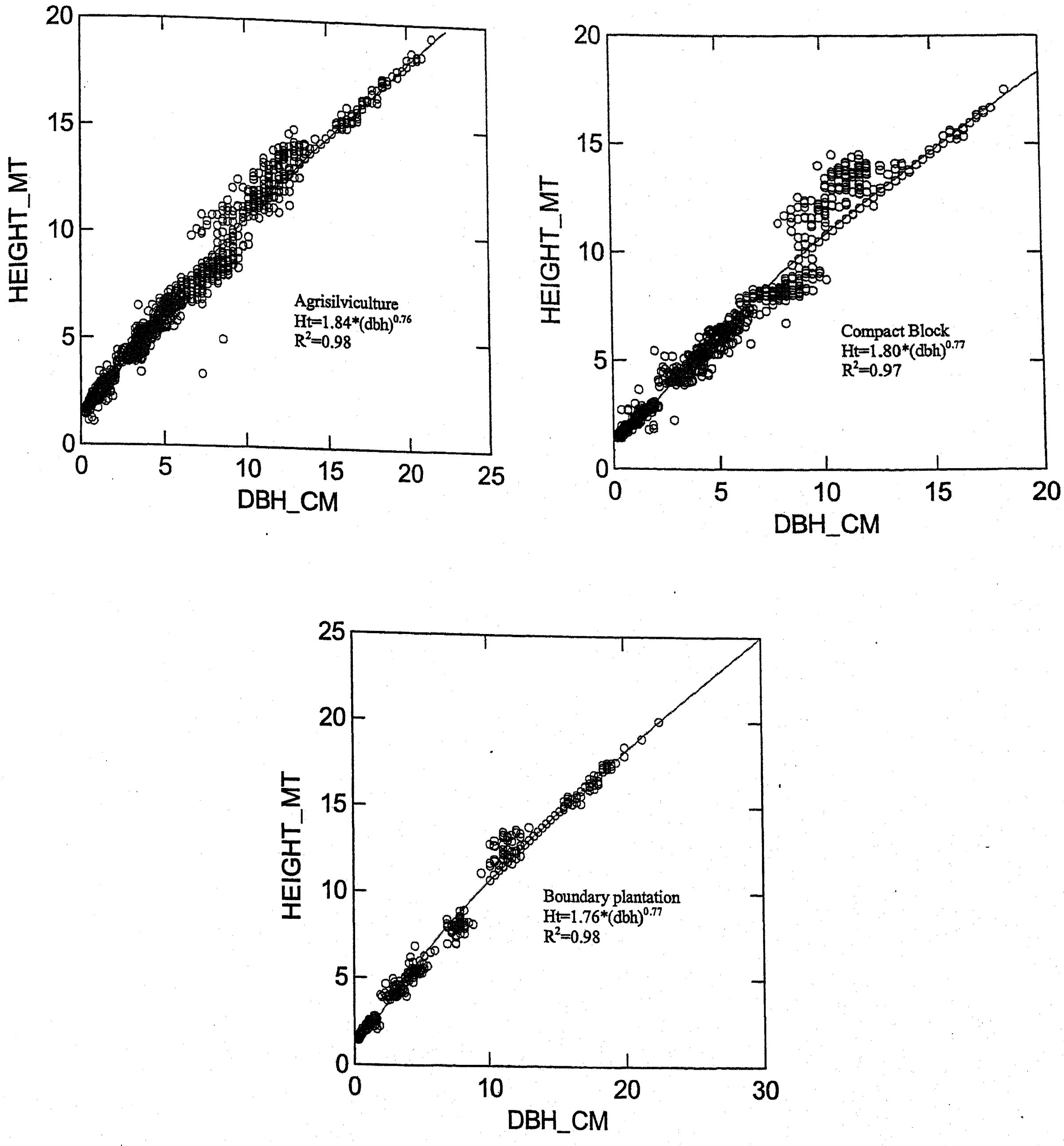
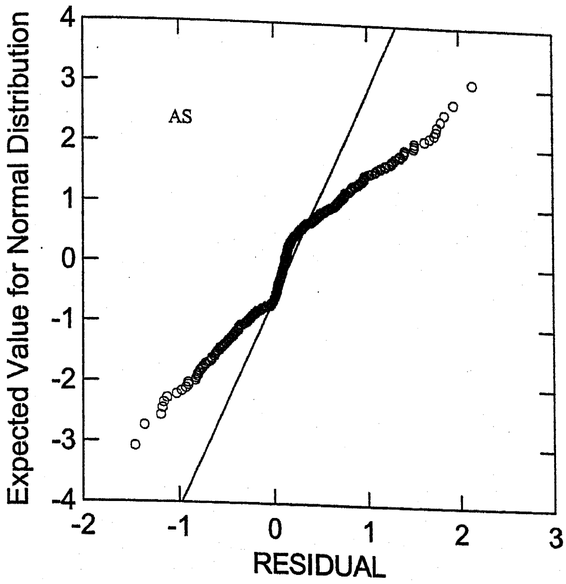
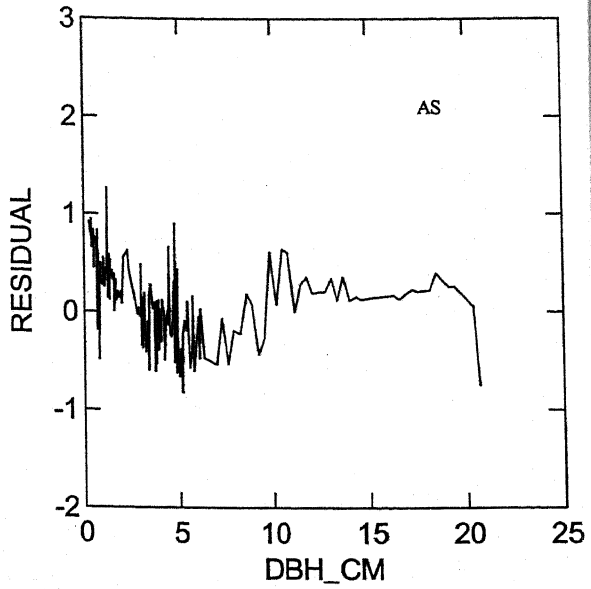


Fig. 7: Various plots of residual diagnostics on the validation dataset for the allometric function under agrisilviculture system.





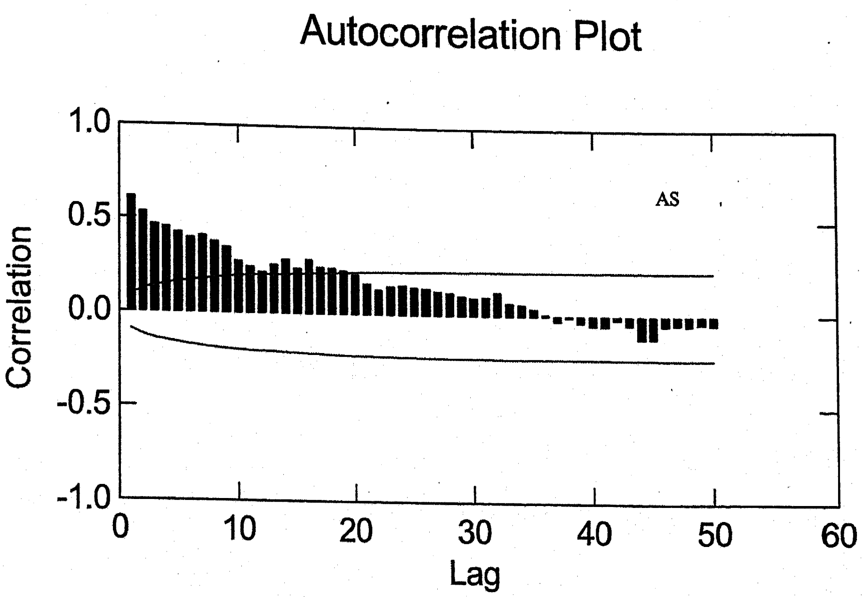


Fig. 8: Various plots of residual diagnostics on the validation dataset for the allometric function fitted under compact block plantations.

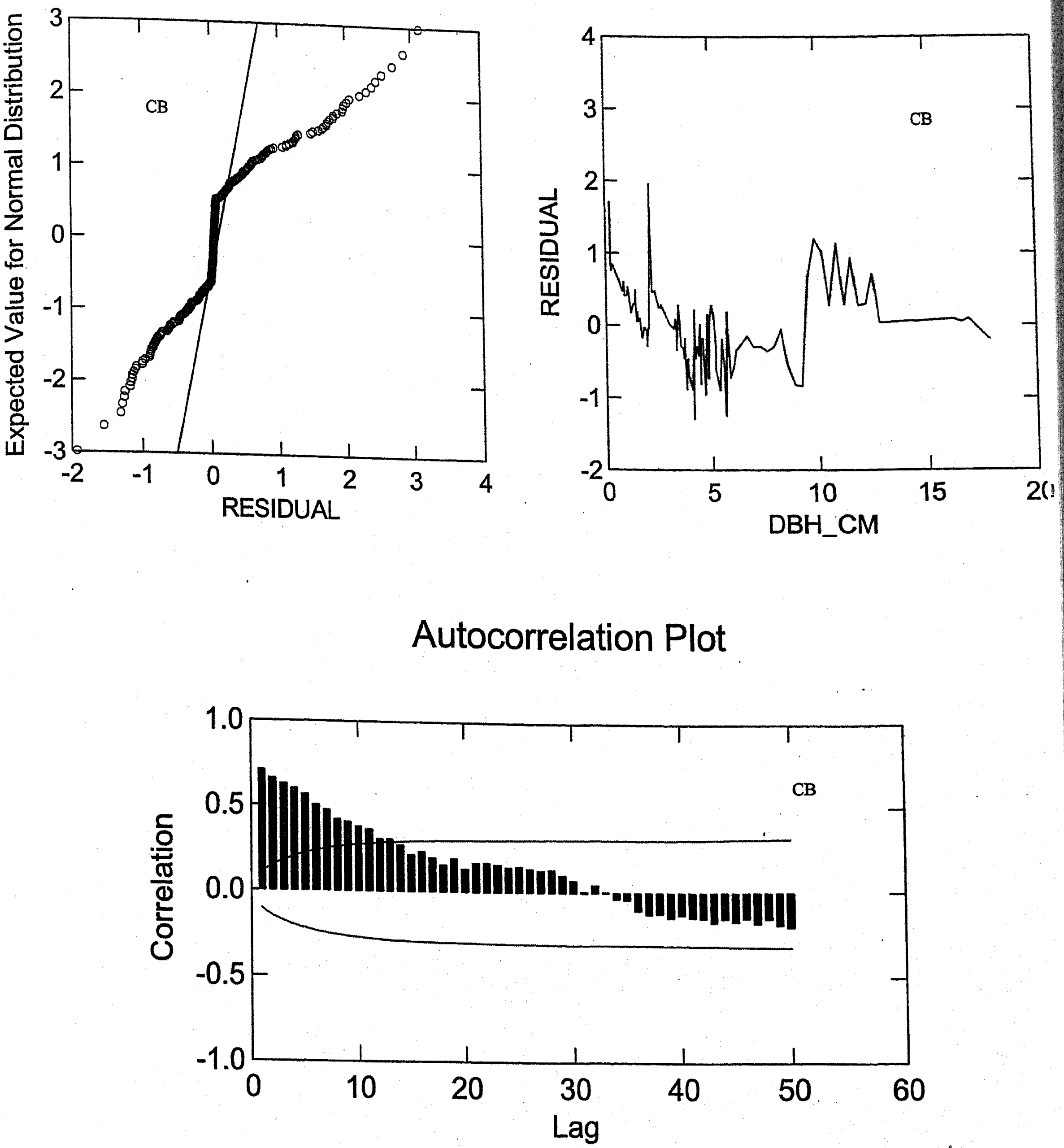
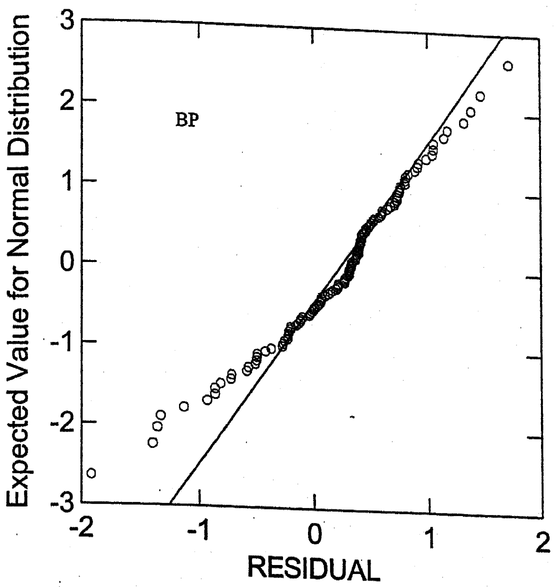
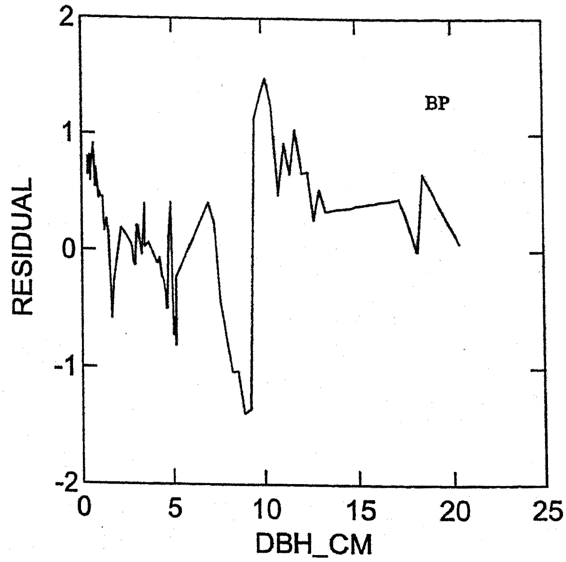


Fig. 9: Various plots of residual diagnostics on the validation dataset for the allometric function fitted under boundary plantations.





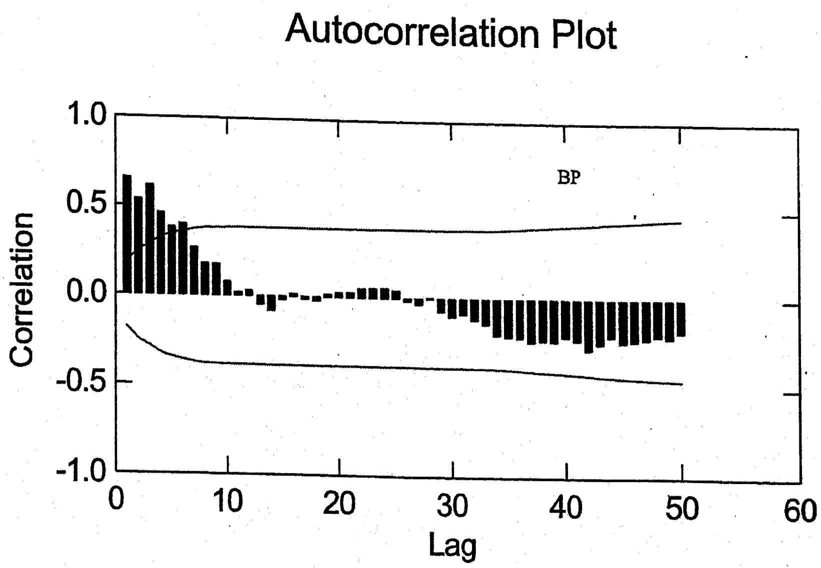
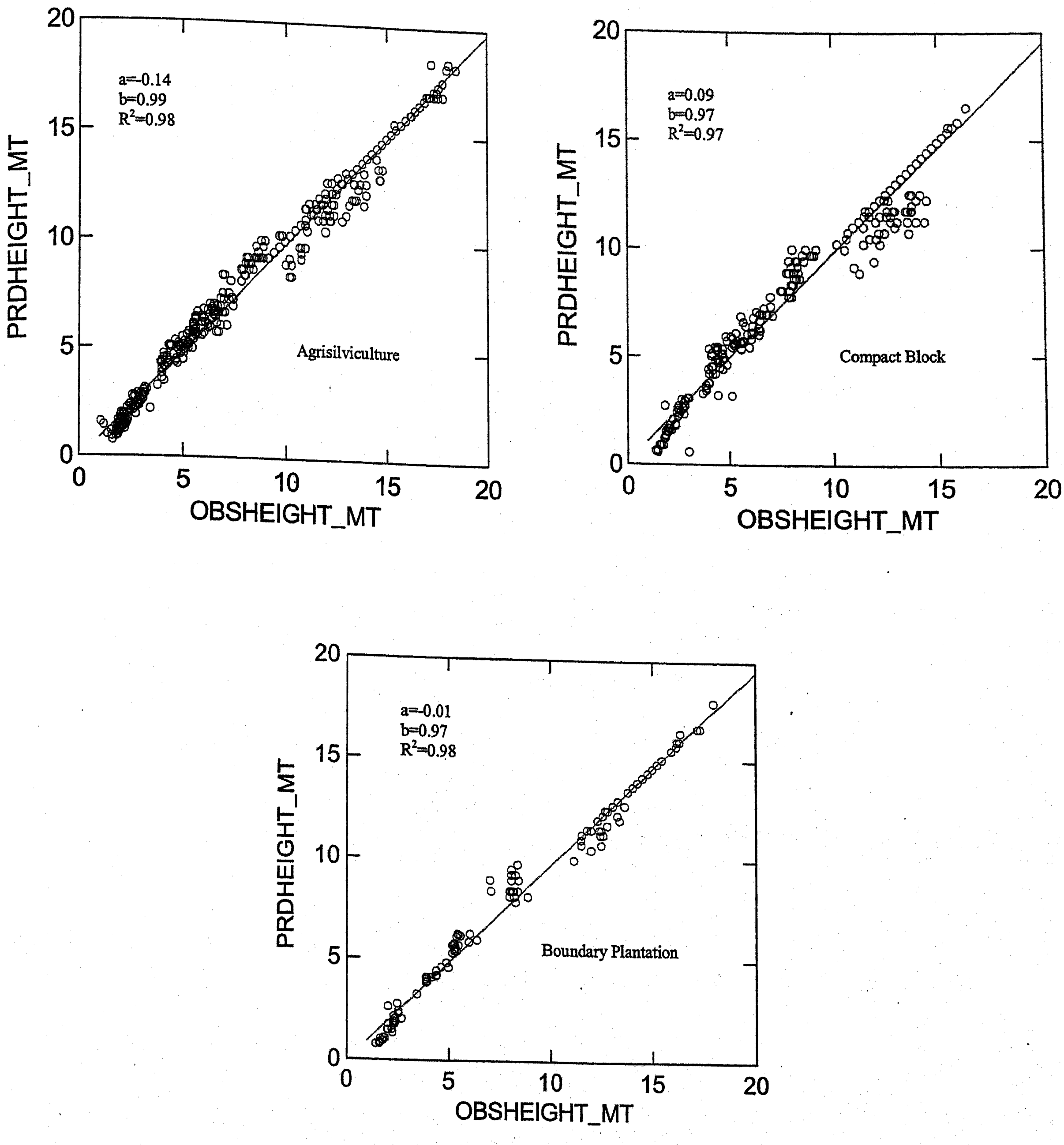


Fig. 10: Graphs of the linear function fitted between the predicted and observed values (predicted height= a+b*observed height) under different agroforestry systems. (For a perfect model, 'a' should be zero and 'b' should be unity along with absolute one R^2-value).



Chapter-5

Modelling and comparison of yield attributes (biomass and volume) of Eucalyptus tereticornis under two contrasting systems [agrisilviculture vs. compact block]

Modelling and comparison of yield attributes (biomass and volume) of *Eucalyptus tereticornis* under two contrasting systems [agrisilviculture vs. compact block]

5.1 Introduction

Eucalyptus is used in short-rotation forestry for pulp production with a rotation length of 10-12 years and a productivity ranging from 10 $m^3 \cdot ha^{-1} \cdot year^{-1}$ to 40 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (mean annual increment of total over bark volume at harvesting) (Antonio *et al.*, 2007[13]). The measurement of tree and stand biomass is of considerable interest today for the study of ecosystem productivity, energy flow, or nutrient and carbon cycling (Turner and Lambert, 2008[214]; Munoz *et al.*, 2008[126]; Mani, and Parthasarathy, 2007[115]; Brown, 2002[23]; Snowdon *et al.*, 2002[184]; Jenkins *et al.*, 2003[87]; Hart *et al.*, 2003[71]; Specht and West, 2003[189]; Zianis and Menuccini, 2003[233]; Zhang *et al.*, 2004[232]; Montagu *et al.*, 2005[125]). Further, renewed interest and increasing attention is being directed towards the need to use woody biomass as a feedstock for bioenergy and byproducts (Volk *et al.*, 2006[221]). Relative to this current fossil fuel feed stocks, biomass production systems can meet the growing raw material and fuel needs, creates less pollution, have positive environmental impacts, and maintain national security (NRC, 2000[127]). In future, short rotation woody crops (SRWC) will be significant source of biomass as more bioenergy and bi byproducts are produced (Berndes, 2001[17]). On the other hand, vegetatively propagated clonal plants developed from a single mother tree having most desirable genetic qualities, are uniform and true to type with all of the genetic qualities of the mother plant. Comparative genetic superiority of each clone and adaptability to different agro climatic and site conditions needs to be confirmed through scientific research trials giving equal conditions of growth and development

of all clones (Lal, 2007[103]). Eucalyptus clones like C3, C6, C7, C10 and C27 developed at Bhadrachalam formed the basis of initial clonal plantations since 1992. Continuous research and development support is most essential for long term development of clonal plantations because of many reasons. Each clone has a specific genetic make up and capacity to tolerate adverse conditions. Because of genetic uniformity of each clone, there can be serious risks of epidemic diseases and insect pest attacks in future if the genetic base of clonal plantations is narrow. Therefore, it is essential to widen the genetic base and diversity of clones by developing a large number of fields tested genetically superior clones for commercial scale plantations (Lal, 2003[102]). The area under agroforestry system of clonal Eucalyptus plantations is expanding fast in many states as farmers are expanding production of timber and pulpwood to meet the growing demand. Therefore, agroforestry research with Eucalyptus as the principal crop needs to be strengthened. Clonal Eucalyptus based agroforestry plantations continue to expand in many states like Andhra, Orissa, Maharashtra, Punjab, Haryana and U.P. Many intercrops both during the Rabi and Kharif season; like oats, barseem, cowpeas, ginger, turmeric and millets have been successfully raised by Pragati Biotechnologies at their research centre at Semi (Punjab) even during 5^{th} year of clonal Eucalyptus plantations. However, further research on better adapted and more shade tolerant crop varieties will be very helpful to farmers growing Eucalyptus under agroforestry system.

Eucalyptus modeling has been used as an indispensable tool for prediction of volume and biomass in forestry and agroforestry studies. A number of studies has been conducted throughout world for estimation of volume growth and biomass components of Eucalyptus species using prediction equations viz. Sochacki *et al.*, 2007[188] for Australia; Andre *et al.*, 2005[11] for Congo; Soares and Tome, 2003[186], Yuancai *et al.,* 2000 and 2001[229 & 230] for Portugal; Ferreira and

Trevisan, 2001[57]; Laclau *et al.*, 2008[100] for Brazil; Bi *et al.,* 2000[21]; Saporito, 2003 [172] for Italy. Regression analysis is commonly applied for developing biomass functions. The predictor variables often used, are diameter at breast height (Malimbwi *et al.*, 1994[114]; Ter-Mikaelian and Korzukhin, 1997[200]; Brown, 2002[23]; Landsberg and Waring, 1997[107]), diameter at stem base or ankle height (Vertannen *et al.*, 1993[220]; Grundy, 1995[65]), crown diameter (Olsson, 1985[135]; Hellden, 1987[72]; Tietema, 1993[211]), and tree height (Stromgaard, 1985[191]; Loomis *et al.*, 1966[110]; Pearson *et al.*, 1984[142]; Bartelink ,1966[16]; Reed and Tome, 1998[160]; Monserud and Marshall, 1999[124]). In most cases the non-linear allometric equation $Y=a*X^b$ is used for modeling the relationship between the biomass (Y) and the predictor variable. Here 'a' and 'b' are regression coefficients estimated using method of least squares on observed data. In India, some work has been recently carried out on Eucalyptus biomass production (Luna and Chamoli, 2008[112]; Prajapati *et al.*, 2006[145]; Faiz *et al.,* 2003[54]; Nagaveni and Vijaylakshmi, 2002[128]; Hunter, 2001[75]; Gill *et al.*, 2001[62] and modeling for *Eucalyptus spp*. (Tewari and Kumar, 2003(a) [201]; Tewari *et al.,* 2002[207]; Thaker and Singh, 2001[208]; Ajit *et al.*, 2000 (a) [3]). However, all these studies have been conducted for pure Eucalyptus plantation only. To the best of our knowledge, no report could be traced on development of growth and yield models for agrisilviculture and their comparison from pure plantations, before the initiation of this study. Accordingly, attempts have been made in this study to develop the prediction equation for estimating above and below ground biomass, total biomass, volume and index of *Eucalyptus tereticornis* for compact block and agrisilviculture plantations under semi-arid conditions.

This chapter concentrates on the twin objectives of quantifying the volume and biomass components of *Eucalyptus tereticornis* over an age series, and to develop

and compare non-linear models for prediction of volume and biomass components on the basis of dbh.

5.2 Materials and methods

5.2.1 Study site

The experiment is being carried out at the Central Research Farm of National Research Centre for Agroforestry, Jhansi which is located at an elevation of 300 m above sea level and is situated between 24°11' N latitude and 78°17' E longitude having tropical semi arid climate with mean annual rainfall of 900 mm. More than 75% of the rainfall is received during monsoon season (last week of June to first week of September). Mean maximum temperature ranges from 47.4° C (June) to 23.5° C (December) and mean minimum temperature from 27.2° C (June) to 4.1° C (December). The soil of the experimental area is sandy loam with low organic carbon, nitrogen, phosphorous and medium to high in potassium.

5.2.2 Experimental details

Four clones of *Eucalyptus tereticornis* (C_3, C_6, C_7 and C_{10}) were obtained from ITC Bhadrachalam, Andhra Pradesh. The field experiment was laid out during August, 2003 in different systems and spacing, namely agrisilviculture (5x4, 10x2, 10x5, 8x4, 5x5 m), compact block (3x3, 2.5x2.5 m) and boundary plantations (2.5m). Three systems (agrisilviculture, compact block and boundary plantation) were employed for growth studies, however trees were harvested only from compact block plantation, because if the trees were harvested from agrisilviculture for growth/yield studies, the design of agrisilviculture study would have changed and accordingly a separate block of agrisilviculture were laid out with the sole purpose of destructive harvesting only. Thus eight trees each from compact block as well as from agrisilviculture were harvested after every six months, starting from the age of six

months upto four years age, for growth and biomass studies. Data on above ground and below ground growth attributes were recorded on each harvested plant. The height reported is in meters, DBH in centimeter, biomass oven dried in kg/tree, volume in m^3/tree and volume index in m^3/ha/year and biomass productivity in tons/ha/year. Since the volume and biomass are not directly comparable under these two systems, because one of the variable, namely tree spacing is also involved in measured data. In fact, both systems have different spacing viz, 5x4m for agrisilviculture and 2.5x2.5m for compact block plantation. To overcome this problem, a more generalized measure called index for volume and biomass productivity has been used. Index is a parameter that does not depends on spacing and all other variables and accordingly these two different systems can very well be compared with this single measure. By the end of four years, a total of 128 cases were processed for total biomass and volume representing 64 harvested trees from both compact block and agrisilviculture respectively. Both datasets were further randomly split into two parts: 80% to estimate the model parameters (estimation dataset) and other 20% to validate the performance (validation dataset). The validation dataset acts as a pseudo independent dataset. The examinations of basic descriptive statistics of the yield (above and below biomass components), volume and growth attributes (height and diameter at breast height) revealed that DBH and total biomass were approximately normally distributed. The total height was not considered for developing the model since usually it is difficult to measure the height of the standing tree with definite accuracy while one can accurately measure the DBH of the standing tree and thus can easily compute the biomass of the standing tree using the developed model. Moreover, DBH alone explained significant amount of variation in volume and biomass components.

5.2.3 Observational methods

5.2.3.1 Above ground biomass and volume calculation

Trees were felled 2-3 cm above the ground. The diameter at breast height (DBH) was recorded by measuring vernier calipers. The total height of felled tree was measured by tape in meter. The leaves were separated and the fresh weights were recorded in kg/tree for leaves, branches and main bole for every one-meter piece. Fresh samples were collected for leaf, branch and bole, oven dried at 70^0c till constant weight and finally dry matter percentages were computed. Fresh weights were multiplied by dry matter percentages to obtain the oven dry biomass of leaf, branch and bole separately. The three components were added to yield the total above ground dry biomass. For the computation of timber volume, stem from bottom to tip of the tree was considered. Diameter was measured on every meter height along the main bole. Newton's formula $V=(d_b+4d_m+d_t)/6)*h$ where d_b denotes diameter at base, d_m denotes diameter at the middle, d_t denotes diameter at the top and h is the length of the log, has been used to compute the volume of meter log and finally added to get the total volume (m^3) of individual tree.

5.2.3.2 Below ground biomass

Although some roots may extent to great depths, the overwhelming proportion of total root biomass was generally found within 75 cm of soil surface. For below ground observations, root system was harvested carefully and biomass of main root, primary root, secondary root and fine root were measured separately. Fresh samples for these components were collected and oven dried at 70^0c till constant weight and finally dry matter percentage were computed. Fresh weights were multiplied by dry matter percentages to obtain the oven dry biomass of all components separately. The component wise biomass was added to get the total below ground dry biomass.

5.2.3.3 Model fitting and Model validation

Non-linear regression was used for fitting various functions on the estimation dataset. For validation purpose, models can be tested in various ways. Firstly, the resampling approach may be suggested (Bi and Hamilton, 199[20], Bi, 1999[18], 2000[19]), secondly, iterative validation procedure may be considered (Williams, 1997[226]). Thirdly, if one has two independent datasets from the same area or population; one set can be used for fitting and the other for validation or, alternatively, if one has only one dataset, it can be divided into two psedo independent sets through random procedure for the purpose (Tiwari and Kumar, 2003 (a)[201]). Here the last approach has been adopted.

Geisser's (1975)[59] 'data splitting' procedure has been applied to validate the model. The complete dataset under each system consisted of 64 points out of which the random sample of 20% data points (13 trees) was selected and reserved as test dataset for validation procedure while the rest 80% of data points (51 trees) were employed for model selection and parameter estimation procedure. Normality of the response variable was verified using Shaiphiro-Wilks test (Rao *et al.*, 1985[154]). Linear regression was initially carried out for estimating biomass/volume through Dbh as explanatory variate, however these models suffers from the problem of negative estimation (Ajit *et al.*, 2000 (b)[8]) of size and therefore non-linear models were attempted and the selection of the model was decided on validation as well as the behavior of model within and outside observed range.

5.2.4 Statistical analysis

The statistical analysis of data was performed using SYSTAT software version 12.01.04 (Wilkinson and Coward, 2007[225]). Analysis of variance (ANOVA) was used to evaluate the differences between clones and systems. The descriptive

statistics (range, mean, skewness, kurtosis and Saphiro wilk statistics) of the growth attributes were initially computed. Non-linear regression was employed to develop relationship between the growth attributes and diameter at breast height as the single predictor variate. Validation of the model was performed initially through residual diagnostics, regression assumptions were verified by plotting graphs between observed, predicted and raw residual values. To further strengthen the validation procedure, simple linear regression was fitted between the observed and predicted values.

5.3 Results and discussions

5.3.1 Biomass production and volume growth

Agrisilviculture system

The mean dbh value in the complete harvested data set was 10.13 cm varying from 0.95 to 19.43 cm whereas the mean height value was 10.67m varying from 2.34 to 18.35 m (Table-1). The tree wise AGB (above ground biomass) ranged from 0.266 to 152.82 kg/tree and the BGB (Below ground Biomass) from 0.11 to 46.52 kg/tree. The average BGB to AGB ratio was 0.17 ranging from a minimum of 0.01 to a maximum of 0.42. Looking to the component wise (bole, branch, leaf) breakup of AGB, the contribution of bole biomass increased from 52% to 85% from 1st to4th year, whereas the contribution of leaf decreased from 34% to 6%. The average contribution of leaf was nearly 10% in the AGB and it almost remained constant over the years (Table 3). The trend of biomass allocation over years has been depicted in Fig. 1. Tree wise volume (m^3/tree) ranged from 0.00033 to 0.221 with a mean value of 0.064. Almost all the growth (height, dbh) and yield attributes (AGB, BGB, total tree biomass,. volume etc.) were normally distributed (normality was tested using shaphiro wilks criterion).

Compact block plantations

The mean dbh value in the complete harvested data set was 7.52 cm varying from 0.95 to 13.69 cm whereas the mean height value was 9.52m varying from 2.41 to 18.30 m (Table-2). The tree wise AGB ranged from 0.30 to 70.05 kg/tree and the BGB from 0.10 to 36.76 kg/tree. The average BGB to AGB ratio was 0.17 ranging from a minimum of 0.08 to a maximum of 0.33. Looking to the component wise (bole, branch, leaf) breakup of AGB, the contribution of bole biomass increased from 56% to 86% from 1st to4th year, whereas the contribution of leaf decreased from 28% to 4%. The average contribution of leaf was about 10% in the AGB and it almost remained constant over the years (Table 3). The trend of biomass allocation over years has been depicted in Fig 1. Tree wise volume (m^3/tree) ranged from 0.00034 to 0.1161 with a mean value of 0.034. Almost all the growth (height, dbh) and yield attributes (AGB, BGB, total tree biomass, volume etc) were normally distributed (normality was tested using shaphiro wilks criterion and smaller p-values (<0.05) indicates normality).

5.3.2 Comparison of yield attributes (biomass and volume) under the two contrasting agroforestry systems

Tree wise average aboveground biomass was more (almost double) in agrisilviculture (45.85 kg/tree) as compared to compact block plantation (23.54 kg/tree). A similar trend was observed for volume also(0.034 m^3/tree in CB and 0.064 m^3/tree in AS. However, if we wish to compare the yield under the two systems at the wider level (plot/field), this tree wise comparison is not sufficient since the tree spacing under the two harvested systems was different (2.5x2.5 in CB and 5x4 m in AS). Thus to compare the systems yield at plot level (per hectare basis), we have to bring yield attributes at the same level (i.e. by eliminating the role of tree spacing). Biomass Index (tons/ha/yr) and Volume Index (m^3/ha/yr) are two such measures for comparing

the systems. The Biomass Index varied from 1.02 to 42.72 tons/ha/yr (with a mean value of 18.09) under compact block plantation and from 0.45 to 24.06 tons/ha/yr (with a mean value of 10.78) under agrisilviculture system. A similar trend was observed for Volume Index ranging from 1.08 to 53.08 m^3/ha/yr (with a mean value of 19.44) under compact block and from 0.33 to 27.82 m^3/ha/yr (with a mean value of 11.30) under agrisilviculture system.

At the age of 4 years, CB showed higher productivity (28.37 m^3/ha/yr and 29.20 tons/ha/yr) as compared to AS (20.20 m^3/ha/yr and 17.87 tons/ha/yr). Few comparable studies have been published on the productivity of *E. tereticornis* like Sudha *et al.*, 2007[193] reported MAI of 10.17 t/ha/yr of aboveground biomass for a four year rotation cycle of eucalyptus in Khamam district of Andhra Pradesh. Considering the allocation of biomass in the below ground component, although some roots were extended to great depths, the overwhelming proportion of the total root biomass was found within 30 cm of the soil surface. Measuring the amounts of biomass in roots and their turnover is an extremely time consuming and costly exercise. Therefore, regression equations are often used to extrapolate aboveground biomass to whole-tree biomass (Kurz *et al.*, 1996[98]; Cairns *et al.,* 1997[27]). However in this study, the trees were completely excavated and therefore exact belowground biomass values were available for development of root biomass models along with aerial biomass models.

5.3.3 Development and validation of yield models

Various non linear functions(allometric and variants of allometric) were attempted to fit estimation data set and the values of R^2 were almost comparable and in some cases R^2 values were on higher side for allometric functions ($Y=a*X^b$), but if we compare the prediction capabilities of these functions outside the observed dbh range, variants

of allometric were well behaved and resulted in reasonable estimation, whereas allometric functions lead to steep over estimation outside the observed dbh range. Accordingly, the parameter estimates of the fitted function (exp(a+b/dbh^1.5) under agrisilviculture and compact block has been compiled in Table-4 and Table-8 respectively. The summary characteristics of the predicted values from the fitted model and observed values in the validation data set under agrisilviculture and compact block have been compiled in Table-5 and Table-9 respectively, whereas the statistics of the residuals under agrisilviculture and compact block are listed in Table-6 and Table-10 respectively. The lower mean value of residuals (1.77 kg/tree for total biomass in agrisilviculture and 0.68 kg/tree in CB respectively) supported by the normality of residuals confirms the appropriateness, of the models in statistical terms. All these models were evaluated for their statistical validation through residual diagnostics for agrisilviculture (Fig. 3), as well as for compact block plantation (Fig. 5). Validation of the model was also ensured by fitting a linear equation (Predicted biomass=a+b* observed biomass) between observed and predicted component (Table-7 and Table-11 for agrisilviculture and compact block respectively). Theoretically, for a perfect fit model the value of 'a' and 'b' must be zero and one respectively, along with a perfect unity R^2-value. The value of 'a' approaching to zero and 'b' approaching to one ensures the good ness of the fitted model (Fig. 2 and Fig. 4 for agrisilviculture and compact block respectively).

The predictive ability of these models was assessed through validation dataset by computing various statistics based on residuals. The models obtained from estimation dataset was applied to the validating dataset for computing the predicted values. The bias is computed as the difference in the predicted and observed values in the validation dataset. The bias mean gives the accuracy of prediction while the variance provides information regarding precision of the prediction. Fig. 2 and Fig. 4 in AS

and CB respectively shows the plots of residual/bias (observed- predicted values) against the predicted values. No clear trend was seen in the residuals, hence it can be said they are not being continuously over or under estimated. The R^2-values for the fitted models were more than 0.79 (for AGB, BGB, total biomass and volume) but on the basis of R^2 alone, the equations should not be recommended for use because they may or may not behave properly if used for prediction outside the observed range. This emphasizes the importance and need of validating properly a model prior to its use. The validation process is necessary so that model can be used with some confidence (Goulding 1979[64], Reynolds and Chung, 1986[162]).

Further more, it would be is desirable a model (preferably allometric) for estimating root biomass directly from tree diameter at breast height. This putative relationship is based on the hypothesis that the growth of roots depends on stem diameter and that the above and belowground stump development of the tree has an allometric balance (Kostler *et al.*, 1968[93]; Santantonio, 1990[171]). The results of this study confirmed that dbh can be used as a simple variable to estimate the root biomass. This facilitates the efforts to determine root biomass without the high cost of excavating the root system.

5.3.4 Comparison of yield index models (biomass and volume) under the two contrasting systems

The recorded trend of the observed Index values over an age sequence has been portrayed in Fig. 7, while the future predictive estimation trend of the fitted model of Index values over the wide range of dbh-values has been depicted in Fig. 6. Index values (for biomass components and volume) were on higher side in CB as compared to AS, however the difference were small in initial years, whereas as the dbh

increases (or age advances) the Index values were significantly greater in CB as compared to AS.

In this index, the role of spacing on yield and growth has been eliminated, since spacing is the major determinant factor in biomass accumulation. Index values (biomass or volume) were on higher side in CB as compared to AS, and it was so simply because the number of trees were more in CB (2.5x2.5m spacing amounting to 1600 trees/ha) than AS (5x4m spacing or 500 trees/ha). Although, this slight decrease in average Index values in AS system, were compensated duly by the intercrop biomass. Infact, if we overall calculate the economics, under the two systems, agrisilviculture system is more viable, economic and sustainable than CB. Moreover, from farmers point of view, agrisilviculture system is more adaptable and acceptable since it starts giving cash dividends (through crop yield) from the first year itself whereas in case of CB the farmers have to wait for a longer duration (at least up to completion of first rotation cycle). Additionally, the AS is sustainable in the sense that the fertilizers and irrigation applied for the crop component sustains the fertility of soil up to a certain extent, whereas in CB it is only the leaf litter which add to the soil fertility, though very little.

Table-1: Summary characteristics of growth attributes for complete harvest dataset under agrisilviculture system.

System	Measured variable	Average (Minimum, Maximum)	Standard deviation	Skewness (Standard error of skewness)	Kurtosis (Standard error of kurtosis)	SW Statistic	SW P-Value
AS	Height (mt)	10.67 (2.34-18.35)	4.454	-0.2722 (0.299)	-0.8875 (0.590)	0.960	0.036
	Dbh (cm)	10.13 (0.95-19.43)	4.728	-0.30132 (0.299)	-0.5973 (0.5904)	0.964	0.064
	Cd(cm)	33.44 (2.49-78.00)	25.12	0.220 (0.299)	-1.562 (0.590)	0.866	0.00001
	Dry bole wt (kg/tree)	37.30 (0.101-134.16)	35.75	1.120 (0.299)	0.4677 (0.590)	0.872	0.00001
	Dry branch wt (kg/tree)	4.55 (0.030-40.23)	5.481	4.564 (0.299)	28.46 (0.590)	0.602	0.00000
	Dry leaf wt (kg/tree)	3.99 (0.135-12.44)	2.467	0.6717 (0.299)	0.9347 (0.590)	0.960	0.0397
	Above ground biomass (kg/tree)	45.85 (0.266-152.82)	40.36	1.0621 (0.299)	0.452 (0.590)	0.887	0.00003
	Belowground Biomass (kg/tree)	14.15 (0.113-46.52)	11.72	0.550 (0.299)	0.343 (0.590)	0.925	0.00084
	Total Biomass	60.01 (0.44-184.34)	50.42	0.848 (0.299)	0.0312 (0.590)	0.911	0.00022
	Volume (m^3/tree)	0.064 (0.00033-0.2219)	0.0592	1.028 (0.299)	0.340 (0.590)	0.8894	0.00003
	Volume index (m^3/ha/yr)	11.30 (0.334-27.82)	7.13	0.429 (0.299)	-0.238 (0.590)	0.960	0.0366
	Biomass index (t/ha/yr)	10.78 (0.450-24.06)	10.78	6.123 (0.299)	-0.549 (0.590)	0.9717	0.0148

Table-2: Summary characteristics of growth attributes for complete harvested dataset under compact block.

System	Measured variable	Average (Minimum, Maximum)	Standard deviation	Skewness (Standard error of skewness)	Kurtosis (Standard error of kurtosis)	SW Statistic	SW P-Value
CB	Height (mt)	9.52 (2.41-18.30)	4.067	-0.314 (0.3015)	-0.929 (0.594)	0.9248	0.00088
	Dbh(cm)	7.52 (0.95-13.69)	3.73	-0.423 (0.301)	-1.102 (0.594)	0.9195	0.00053
	Cd(cm)	25.59 (2.23-56.00)	19.84	0.1483 (0.301)	-1.750 (0.594)	0.8334	0.0000
	Dry bole wt (kg/tree)	18.59 (0.125-59.68)	16.39	0.7310 (0.301)	-0.176 (0.594)	0.9105	0.00023
	Dry branch wt (kg/tree)	2.13 (0.03-7.18)	1.87	0.957 (0.3015)	0.312 (0.594)	0.9021	0.00011
	Dry leaf wt (kg/tree)	2.82 (0.12-10.23)	2.17	0.864 (0.3015)	0.9317 (0.594)	0.9287	0.00130
	Above ground biomass (kg/tree)	23.54 (0.30-70.05)	19.52	0.599 (0.3015)	-0.394 (0.594)	0.9218	0.00066
	Belowground Biomass (kg/tree)	7.75 (0.10-36.76)	7.30	1.379 (0.301)	2.905 (0.594)	0.878	0.00002
	Total Biomass	31.29 (0.31-106.81)	26.22	0.682 (0.301)	-0.029 (0.594)	0.926	0.00105
	Volume (m^3/tree)	0.034 (0.00034-0.1161	0.029	0.727 (0.3015)	-0.033 (0.594)	0.9165	0.00040
	Volume index (m^3/ha/yr)	19.44 (1.08-53.08)	13.36	0.385 (0.3015)	-0.448 (0.594)	0.945	0.00715
	Biomass index (t/ha/yr)	18.09 (1.02-42.72)	11.68	0.206 (0.3015)	-0.740 (0.594)	0.945	0.00789

Table-3: Component wise allocation of biomass over an age series for both systems (agrisilviculture and compact block).

Systems	Year	% Breakup of total biomass		% Breakup of total Aboveground biomass			BGB-AGB ratio	Net Biomass Productivity (tons/ha/yr)	Net Volume Productivity (m^3/ha/yr)
		AG	BG	Bole	Branch	Leaf			
AS	1	7.419 (76%)	2.297 (24%)	4.160 (56%)	1.206 (16%)	2.053 (28%)	0.15	4.85	3.87
	2	37.73 (69%)	16.85 (31%)	27.32 (72%)	4.938 (13%)	5.471 (15%)	0.22	13.64	13.12
	3	50.75 (68%)	24.86 (32%)	44.16 (86%)	3.29 (7%)	3.29 (7%)	0.28	15.60	16.30
	4	116.57 (82%)	26.12 (18%)	99.94 (86%)	12.21 (10%)	4.41 (4%)	0.14	17.87	20.20
CB	1	1.840 (79%)	0.495 (21%)	0.960 (52%)	0.2672 (14%)	0.613 (34%)	0.11	3.73	3.81
	2	22.59 (80%)	5.272 (20%)	15.823 (70%)	2.2887 (10%)	4.481 (20%)	0.11	22.29	22.17
	3	40.48 (75%)	13.41 (26%)	31.55 (78%)	4.19 (11%)	4.73 (12%)	0.20	28.74	27.74
	4	51.33 (72%)	22.03 (28%)	43.76 (85%)	4.40 (8%)	3.16 (6%)	0.22	29.2	28.37

Table-4: Values of coefficients for different biomass components obtained for fitting dataset of agrisilviculture $Y=e\ (a+b/x^{1.5})$ (Y-component biomass (kg/tree) and X-dbh (cm)

Biomass Component (ag)	Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
				Lower	Upper	
Bole	a	5.99	0.069	5.85	6.13	0.95
	b	-94.32	3.902	86.49	102.15	
Branch	a	4.14	0.351	3.44	4.85	0.47
	b	-109.74	20.63	68.34	151.41	
Leaf	a	1.80	0.118	1.567	2.04	0.37
	b	-8.20	3.717	0.739	15.66	
Total Aboveground	a	6.05	0.064	5.92	6.18	0.96
	b	-87.52	3.551	80.39	94.64	
Total Belowground	a	4.21	0.129	3.95	4.47	0.79
	b	-55.28	6.318	42.60	67.96	
Total biomass	a	6.15	0.056	6.04	6.26	0.96
	b	-78.97	3.024	72.90	85.04	
Volume	a	-0.50	0.069	-0.641	-0.362	0.95
	b	-87.12	3.806	79.48	94.76	
Index volume (m^3/ha/yr)	a	3.70	0.081	3.53	3.86	0.87
	b	-43.32	3.756	35.78	50.86	
Index biomass (t/ha/yr)	a	3.37	0.084	3.20	3.54	0.82
	b	-31.68	3.612	24.43	38.93	

Table-5: Summary statistics of the predicted and observed values in the validating dataset (agrisilviculture)

Measured variable (pooled)	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
dbh	8.59 (0.95-16.88)	5.84	0.214 (0.687)	-1.612 (1.334)	0.916	0.332
Obs. aboveground	38.44 (0.26-121.42	43.69	1.00 (0.687)	-0.296 (1.334)	0.838	0.042
Pred. aboveground	37.94 (0.002-120.06	48.66	0.851 (0.687)	-1.100 (1.334)	0.779	0.008
Obs. belowground	12.37 (0.18-41.86)	14.62	1.07 (0.687)	0.021 (1.334)	0.821	0.026
Pred. belowground	11.08 (0.003-30.35)	12.75	0.562 (0.687)	-1.662 (1.334)	0.801	0.015
Obs. total biomass	50.81 (0.44-149.14)	55.65	0.770 (0.687)	-1.062 (1.334)	0.836	0.0395
Pred. total biomass	49.04 (0.001-150.10)	61.39	0.783 (0.687)	-1.246 (1.334)	0.785	0.0096

Table-6: Descriptive statistics of residuals in the validation dataset (agrisilviculture).

Residuals	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
Aboveground	0.49 (-15.40-12.85)	8.72	-0.539 (0.687)	-0.377 (1.334)	0.954	0.723
Belowground	1.35 (-3.18-7.6)	3.09	0.478 (0.687)	1.017 (1.334)	0.950	0.670
Total biomass	1.77 (-21.25-9.71)	9.18	-1.89 (0.687)	4.655 (1.334)	0.765	0.0050

Table-7: Component wise summary characteristics of model parameters (agrisilviculture)

System (Linear)	Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
				Lower	Upper	
Total aboveground	a	-4.35	3.45	-12.31	3.61	0.97
	b	1.10	0.061	0.95	1.24	
Total belowground	a	1.49	3.434	-6.42	9.41	0.73
	b	0.98	0.209	0.49	1.46	
Total biomass	a	6.68	2.990	-0.20	13.58	0.98
	a	0.89	0.039	0.80	0.99	

Fig. 1: Year wise allocation of biomass in different above and below ground components under two agroforestry systems.

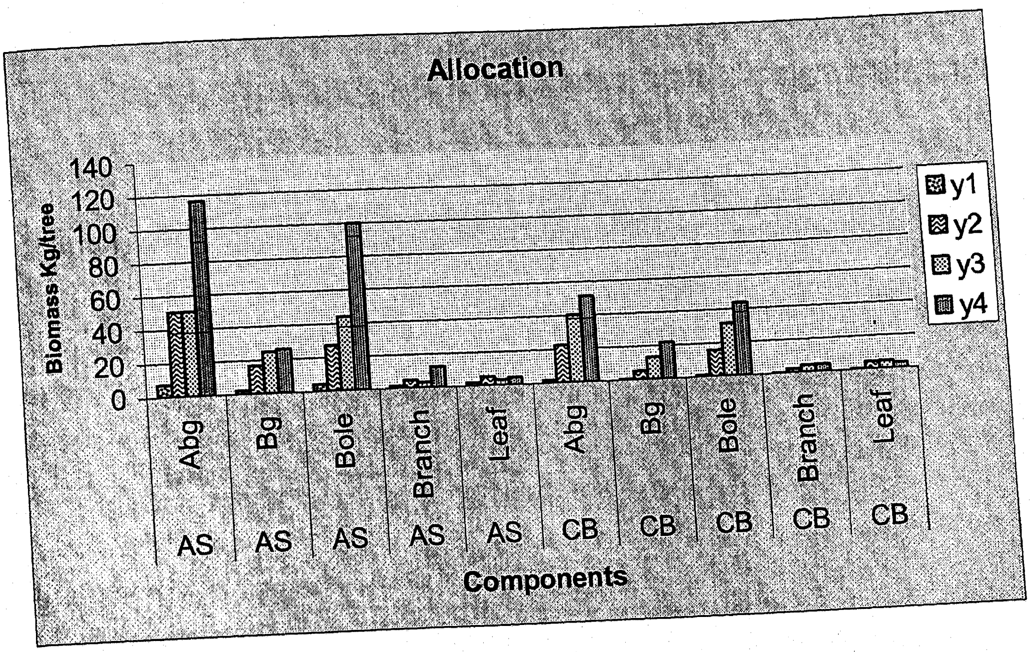


Fig. 2: Graphs of the linear function fitted between the predicted and observed values (predicted component= a+b*observed component) under agrisilviculture.

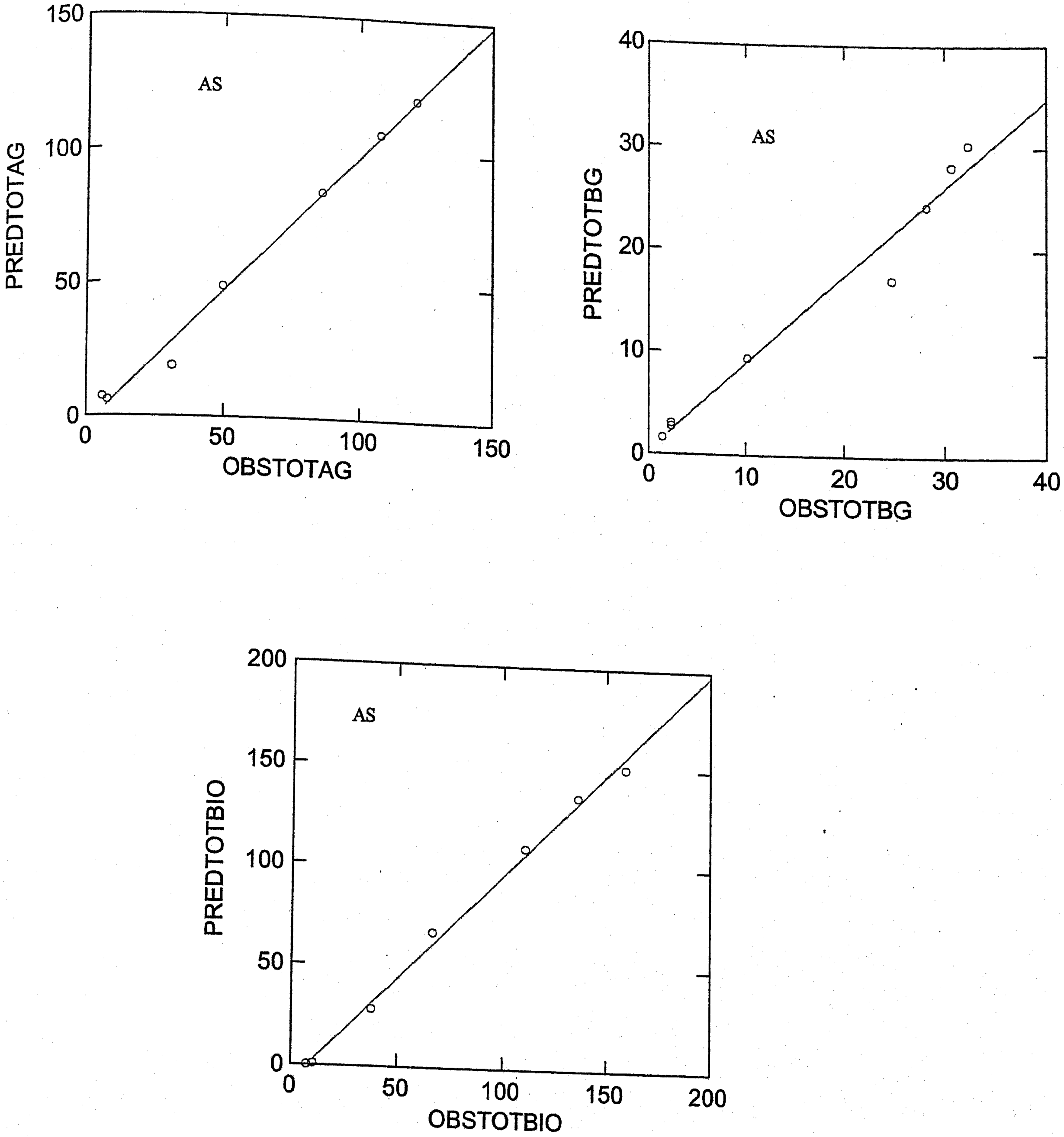


Fig. 3: Various plots of residual diagnostics on the validation dataset for the non-linear function under agrisilviculture system.

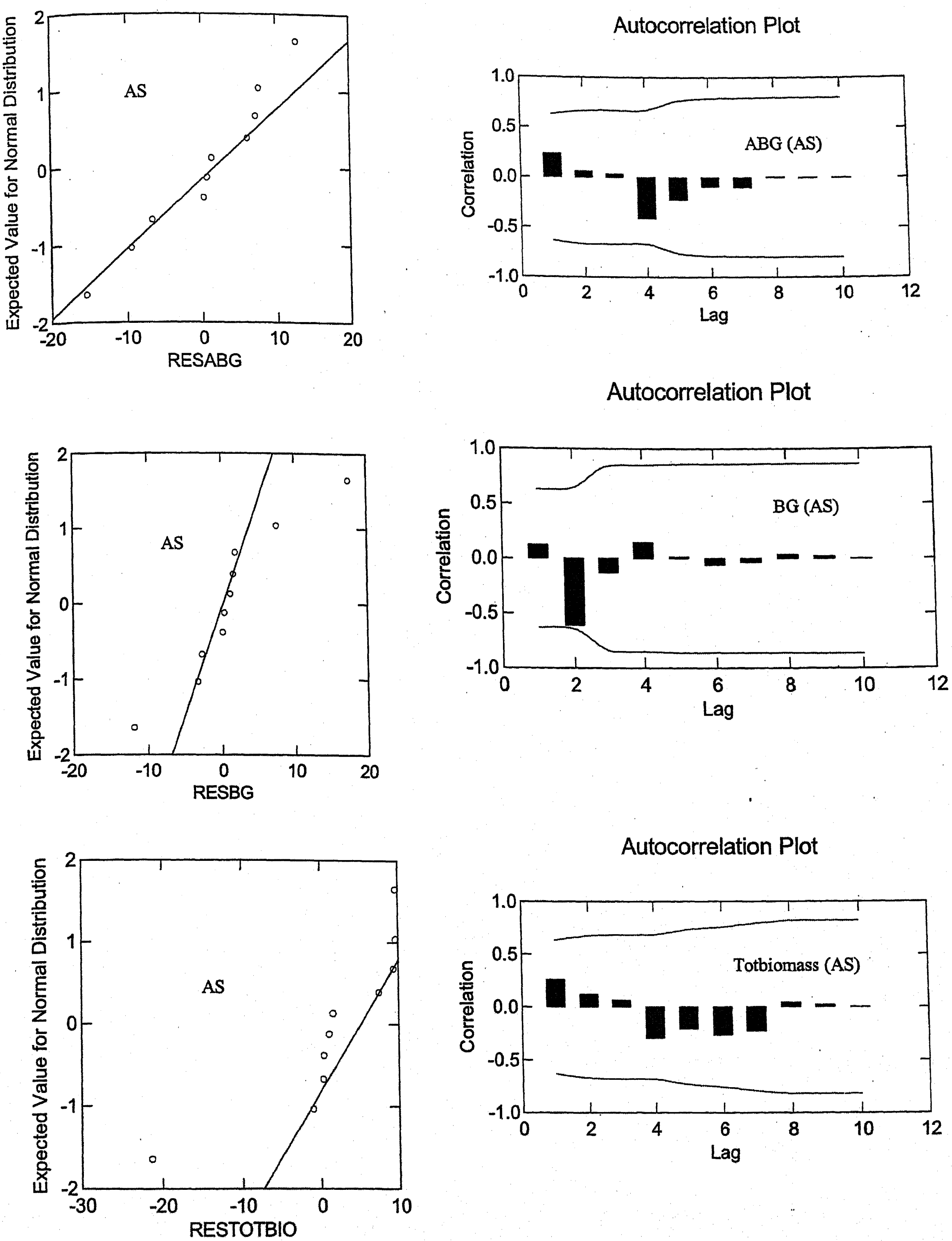


Table-8: Values of coefficients for different biomass components obtained for fitting dataset of compact block ($Y=e\ (a+b/x^{1.5})$ (Y-component biomass (kg/tree) and X-dbh (cm) .

Biomass Component	Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
				Lower	Upper	
Bole	a	5.09	0.1116	4.87	5.32	0.92
	b	-56.37	3.929	-64.26	-48.47	
Branch	a	2.14	0.252	1.633	2.64	0.45
	b	-30.85	8.015	-46.96	-14.75	
Leaf	a	1.89	0.185	1.521	2.26	0.48
	b	-16.81	5.236	-27.33	-6.29	
Total Aboveground	a	5.11	0.1178	4.876	5.34	0.91
	b	-49.41	4.054	-57.56	-41.26	
Total Belowground	a	4.57	0.2210	4.131	5.01	0.79
	b	-68.15	8.040	-84.31	-51.99	
Total biomass	a	5.53	0.125	5.281	5.78	0.90
	b	-53.76	4.365	-62.53	-44.99	
Volume	a	-1.13	0.084	-1.30	-0.96	0.96
	b	-58.88	3.000	-64.91	-52.85	
Index volume (m^3/ha/yr)	a	4.35	0.108	4.139	4.57	0.87
	b	-32.25	3.483	-39.26	-25.25	
Index biomass (t/ha/yr)	a	3.99	0.110	3.773	4.217	0.81
	b	-23.24	3.339	-29.25	-16.53	

Table-9: Summary statistics of the predicted and observed values in the validation dataset (compact block).

Measured variable	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
dbh	5.77 (1.11-12.74)	4.68	0.266 (0.637)	-1.975 (1.2322)	0.813	0.0135
Obs. aboveground	18.84 (0.33-67.42)	23.06	0.994 (0.637)	-0.0918 (1.2322)	0.807	0.0110
Pred. aboveground	17.58 (0.003-55.89)	21.37	0.651 (0.637)	-1.348 (1.232)	0.787	0.0068
Obs. belowground	5.42 (0.10-16.08)	6.44	0.748 (0.637)	-1.181 (1.232)	0.787	0.0068
Pred. belowground	5.98 (0.001-21.57	7.74	0.901 (0.637)	-0.568 (1.232)	0.783	0.0061
Obs. total biomass	24.26 (0.52-79.38)	28.79	0.781 (0.637)	-0.895 (1.232)	0.809	0.0120
Pred. total biomass	23.58 (0.002-77.30)	29.10	0.708 (0.637)	-1.187 (1.232)	0.787	0.0067

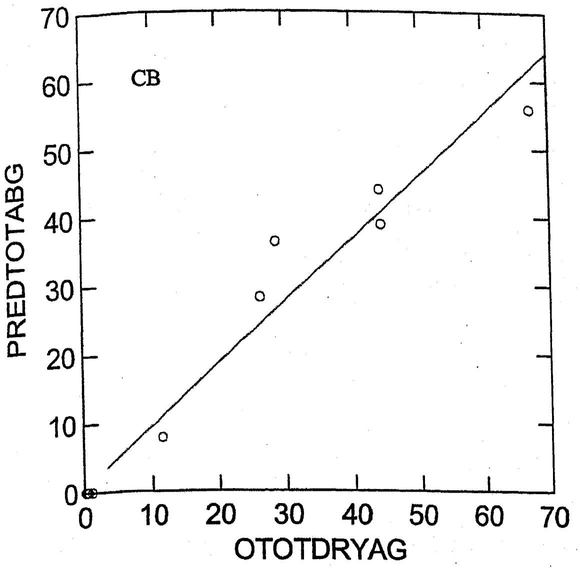
Table-10: Descriptive statistics of residuals in the validation dataset (compact block).

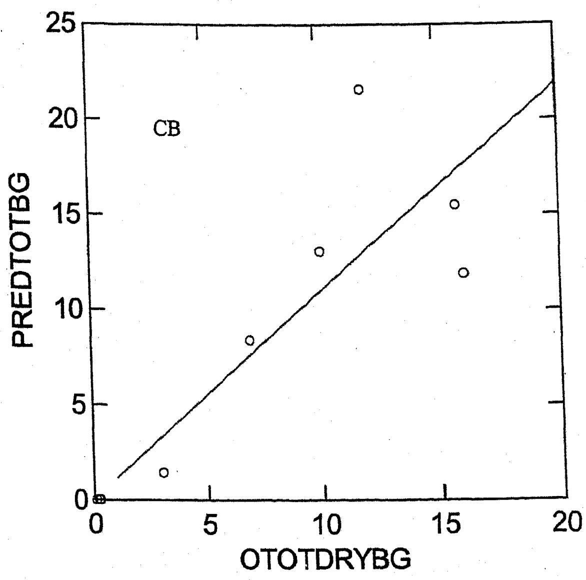
Residuals	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
Aboveground	1.25 (-7.57-11.52)	4.48	0.544 (0.637)	2.815 (1.232)	0.873	0.0731
Belowground	-0.561 (-9.61-4.19)	3.30	-1.917 (0.637)	5.574 (1.232)	0.757	0.0032
Total biomass	0.681 (-3.51-5.54)	2.40	-0.161 (0.637)	1.440 (1.232)	0.873	0.0723

Table-11: Validation of non-linear model by fitting a linear equation between predicted and observed values (predicted component =a+b*observed component) on validation dataset (20%) under compact block plantation.

System (linear)	Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
				Lower	Upper	
Total aboveground	a	0.42	1.586	-3.105	3.963	0.96
	b	0.91	0.054	0.788	1.032	
Total belowground	a	0.07	1.311	-2.846	2.998	0.82
	b	1.08	0.159	0.733	1.445	
Total biomass	a	-0.85	0.967	-3.015	1.295	0.99
	a	1.00	0.026	0.948	1.066	

Fig. 4: Graphs of the linear function fitted between the predicted and observed values (predicted component= a+b*observed component) under compact block.





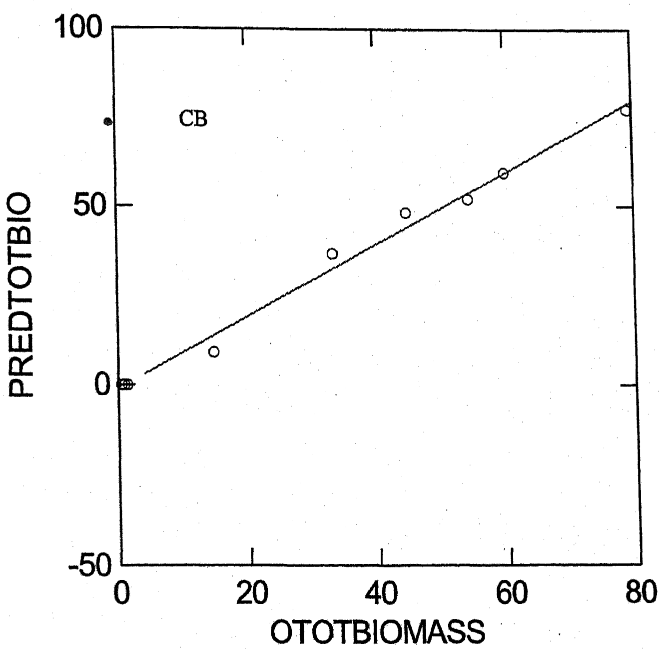


Fig. 5 : Various plots of residual diagnostics on the validation dataset for the non-linear function under compact block plantation.

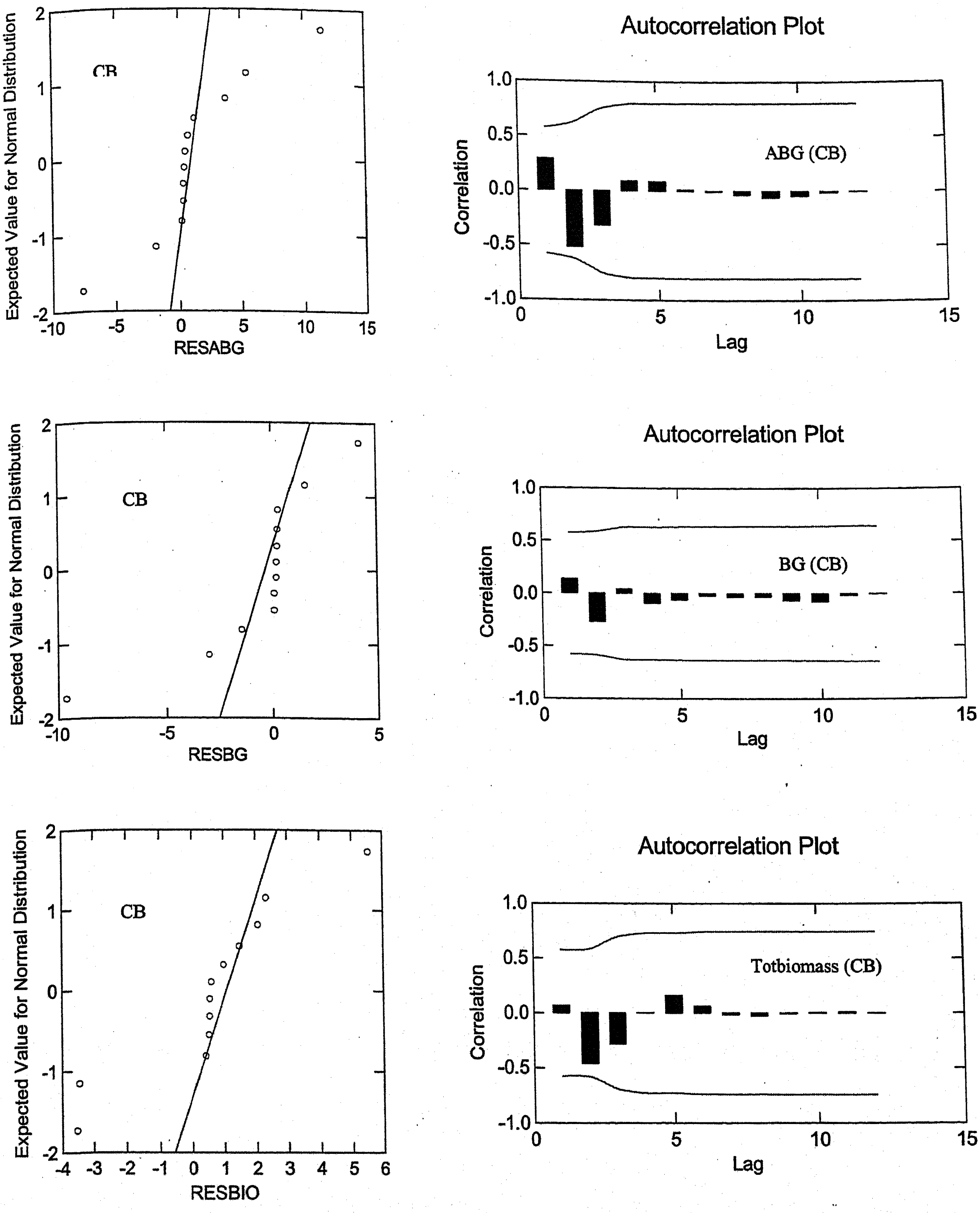


Fig. 6: Predicted trend of Eucalyptus volume and biomass yield over a wide range of dbh under agrisilviculture (AS) versus compact block (CB) systems.

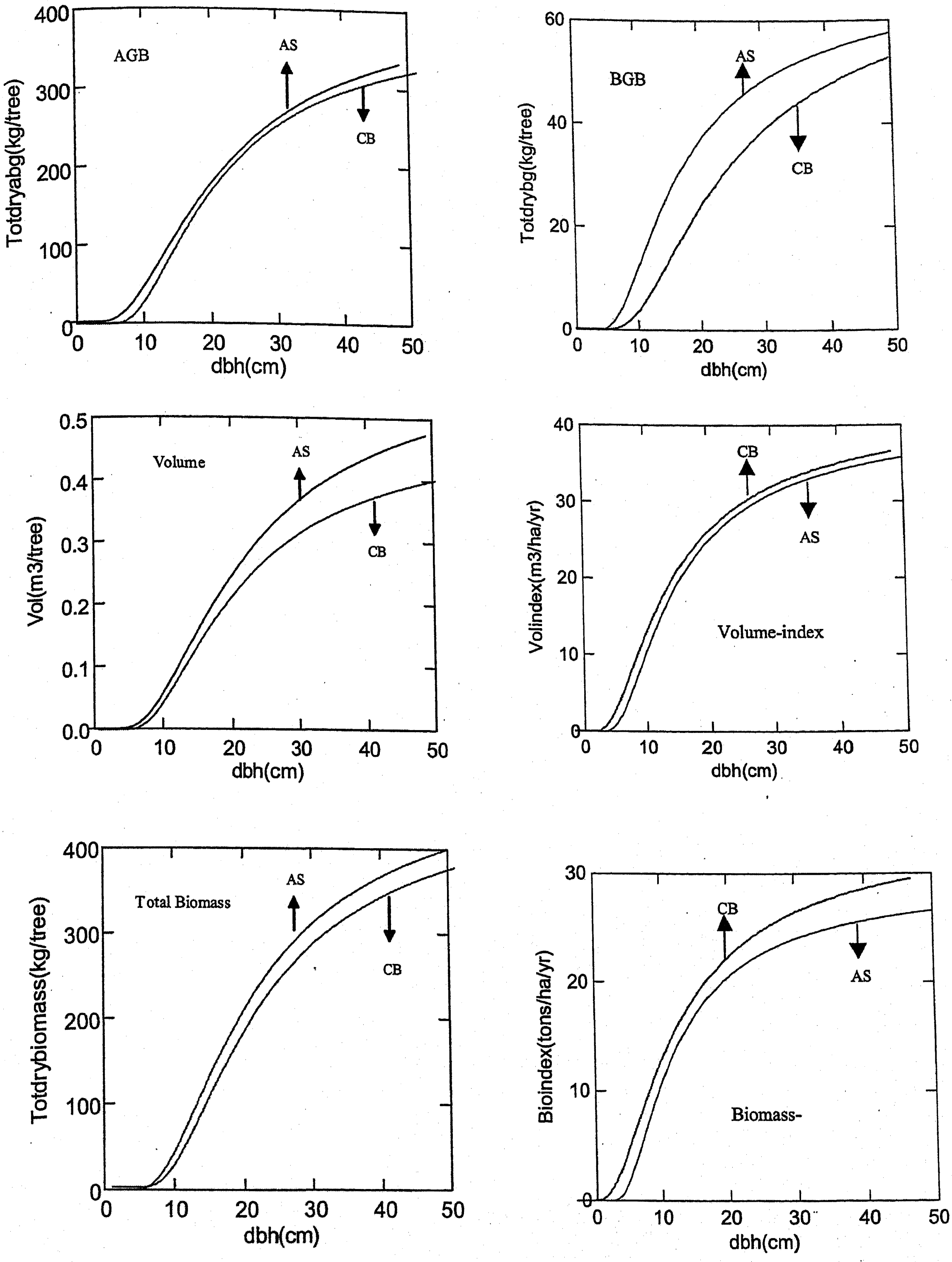
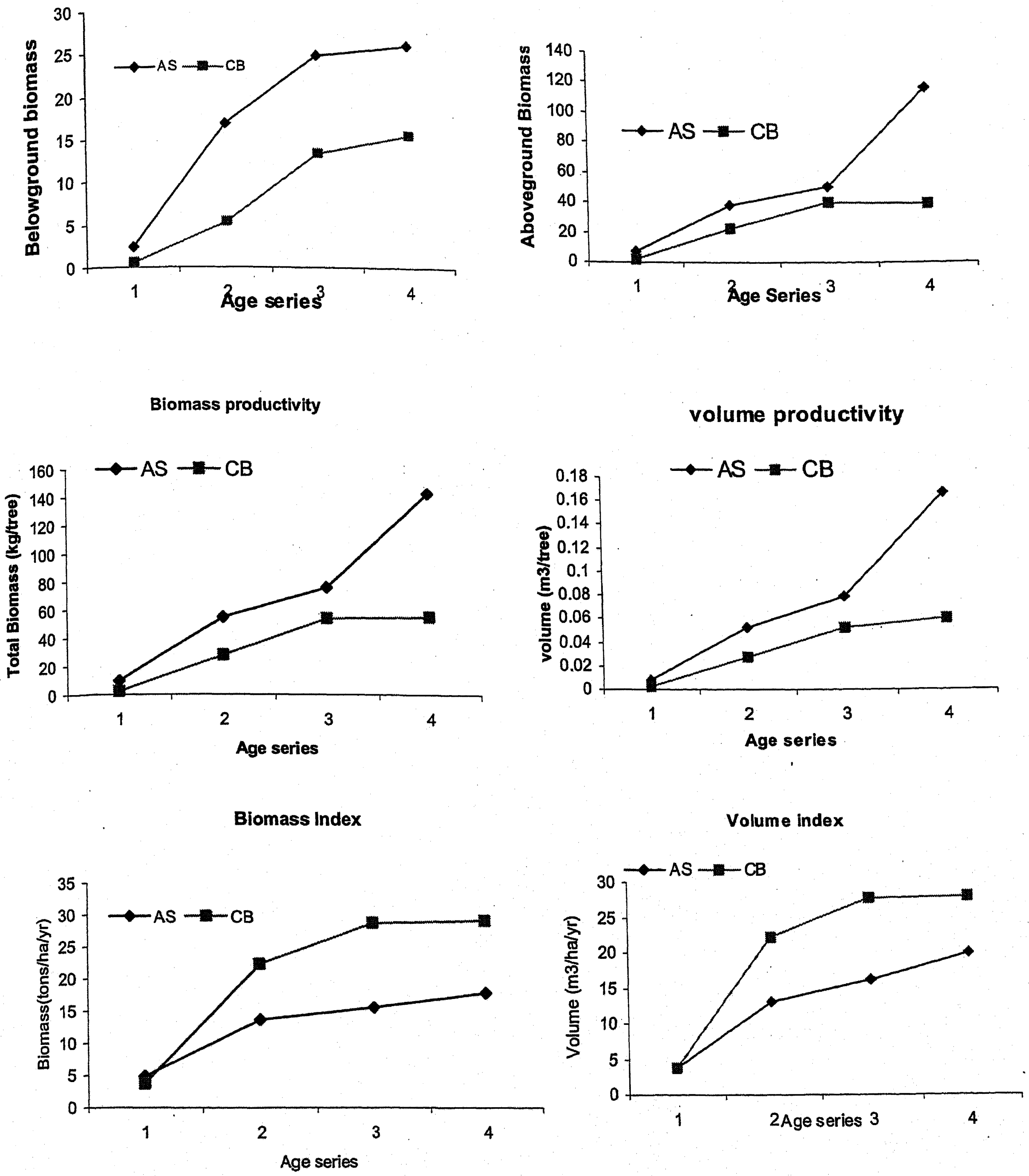


Fig. 7: Observed trend of Eucalyptus volume and biomass yield under agrisilviculture (AS) versus compact block systems (CB) over an age series.



Chapter-6

Development of consolidated yield models (volume and biomass) of Eucalyptus spp. at national level by employing primary, secondary and simulated data

Development of consolidated yield models (volume and biomass) of Eucalyptus spp. at national level by employing primary, secondary and simulated data.

6.1 Introduction

Among the fast growing species in India, eucalyptus have assumed great importance in large scale plantation programme to meet the rising demands of wood for local and industrial consumption (Singh *et al.*, 1992[180]). Eucalyptus species has been widely accepted by the farmers in India not only in pure plantations but also even with more enthusiasm along with crops i.e. in agroforestry because of its short rotation cycle, rapid growth and excellent fibre qualities. Eucalyptus species has also been recommended among the six tree species to be used for agroforestry in India as identified by the Planning Commission through its "Task Force on Greening India" that published its report in June, 2001. Fast-growing plantations will be required to fill in the shortfall of supply from natural forest. The yields that have been obtained in existing plantations (often with species exotic to the site) have typically been many times greater than those in natural forests. Thus, plantations have, additionally, the possibility of satisfying the current demand for wood from a much smaller land area than at present. Rapid and easily implemented methods are needed for the assessment of standing biomass to estimate the degree of carbon sequestration by forest ecosystems. Equations, that provides accurate predictions of volume, without local bias over the entire range of diameter are one of the basic building blocks of a forest growth and yield simulation system (Bi and Hamilton, 1998[20]). Development of sound management practice is one of the major priorities of the forestry sector. The most often used, for determining individual tree volume or biomass are the allometric relationships (Causton, 1985[31]; Reed and Green, 1985[159]; Thornley and Johnson,

1990[210]; Reed and Tome, 1998[160]; Whittaker and Woodwell, 1968[223]). Normally, the volume or biomass of a tree is predicted as an equation of some easily measured variable, such as diameter at breast height (dbh or D) or height (H) or a combination of them say D^2H.Whenever there is need for estimating the biomass of individual trees, the abundance of currently available predictive equations provides an alternative to the destructive sampling of trees for developing local equations. Comprehensive collections of stand-specific biomass equations are available in the literature (for North America Ter-Mikaelian and Korzukhin 1997[200], Jenkins *et al.*, 2004[86]; for Australia Eamus *et al.*, 2000[51], Keith *et al.*, 2000[90], Snowdon *et al.*, 2000[183] and for Europe Zianis *et al.*, 2005[234]). Most published biomass equations were developed using trees sampled from specific study sites or from sites that represent small regions only. As a result, use of existing volume or biomass equations with forest inventory data at large spatial scales is unreliable because the equations of previous studies may be site-specific, often disorganized and sometimes inconsistent (Pastor *et al.*, 1983/1984[140]; Jenkins *et al.*, 2003[87]; Wirth *et al.*, 2004[228]). Furthermore, unless an equation was developed exclusively for the species and study region of interest under conditions typical for the study site, it is impossible to know which equations to choose for a particular species and site. Reliable models of tree-level biomass to be used at large spatial scales are available mainly for Scandinavia and were compiled by Marklund (1987)[116]. Thus there is a need to develop generalized biomass and volume equations of eucalyptus, that will hold good at a wider spatial level in the country.

There may be additional value in deriving generalized equations for comparing different regions, since it is important to know that inconsistencies between regions are not due solely to the application of different regression equations, which yield contrasting values even for the same dataset but do not significantly vary among

themselves (Pastor *et al.,* 1983/1984)[140]. Despite these inconsistencies, or perhaps because of them, the need is clear for a consistent method and for generalized equations to estimate forest biomass at large scales (Jenkins *et al.,* 2003)[87].

Biomass equations or volume equations are now widely developed in forestry and agroforestry for both scientific and industrial purposes. Crow and Schlaegel (1988)[41] cautioned that there is an inherent danger in using site specific allometric equations as they are generally not applicable to other locations. Thus, site-specific allometric equations are of limited utility beyond the site for which they were developed as they cannot be extrapolated to other locations or throughout the biogeography range of a particular tree species with a high degree of confidence (Law *et al.,* 2001)[108]. Pastor *et al.,* (1983/1984)[140] developed statistical approach to develop generalized allometric equations that are of greater utility to forest ecologists and plant scientists because they are usually valid for a large portion or whole of a tree species' biogeographic range. The development of generalized allometric equations is essential to the work of other forest ecologists, plant scientists, and biogeographers, especially for wide-ranging and economically important tree species, because they allow for comparisons of biomass and production among sites (Pastor *et al.*, (1983/1984)[140] and provide the requisite data for model input. Since most scientists have not published the raw data from which their volume or biomass equations were developed. However, several authors reported that generalized regressions developed from field data can reasonably predict the biomass or volume of trees from other sites (Landsberg and Waring, 1997[107]; Schmitt and Grigal 1981[173]; Wirth *et al.,* 2004[228]).

The purpose of this study was to develop a generalized allometric equation for estimating and predicting the aboveground biomass and Volume of Eucalyptus

species on the basis of dbh and validate the derived equation using a separate set of destructively sampled Eucalyptus trees. To date, no known study in India has derived a generalized allometric equation predicting eucalyptus volume or biomass on the basis of dbh from site-specific regressions throughout its biogeographic range, despite its importance for other work in the forestry and the plant sciences. Accordingly attempts has been made in this chapter to develop and validate generalized equations that are applicable for a wide range of site and climatic conditions. The resulting equation will be of interest and use to researchers, planners and mangers to estimate volume accumulated by the standing eucalyptus trees at any stage/ age by simply measuring the dbh alone.

6.2 Data

Site-specific aboveground biomass (dry weight) and volume equations have been developed for eucalyptus species in different parts of the country. Equations relating volume of the stem or biomass of the tree component (stem, branches, foliage and total aboveground) to dbh were compiled (Table-1) from the comprehensive literature published in journals pertaining to Indian context only. Several equations based on independent tree samples from different sites were reported, all were included in this study. In the present study we analyzed the regression equations from following states of India: Uttar Pradesh, Uttrakhand, Karnataka, Rajasthan, Punjab and Tamil Nadu. In accordance with the methodology set forth by Pastor *et al.*, 1984, five equally spaced points were generated from each of the compiled regression (Table-1) and volume/AGB was computed. These points covered the range of dbh values specific to each regression, and were then used to generate a new simulated dataset. Thus for each study, five volume/AGB points were computed, yielding a total of 112 points in the simulated dataset from which the generalized allometric regression equation was derived. This method ensures that each site-specific allometric equation

was weighed equally in the formulation of the generalized equation. Validation of the model was performed using a geophysically and statistically independent datasets both for volume and aboveground biomass. The validity of the mathematical and physical assumptions used in developing a model and estimating the coefficients is less open to question if the model gives accurate predictions of new data. In effect, the collection of new data provides an overall check on the entire model construction process.

6.3 Statistical analysis

Systat-12 statistical software (Wilkinson and Coward, 2007[225]) was used for computation of descriptive statistics (mean, standard deviation, skewness, kurtosis, Shaphiro Wilk's statistic for normality testing etc) and fitting of different equations (estimates of model parameters, asymptotic standard error of estimate, confidence interval, R^2 values etc) and plotting of various graphs pertaining to residual diagnostics (probability plot of residuals, auto correlation plots of residuals, plot of residuals against their expected values, plot of residual against independent variate).

Table-1: Site-specific published equations in India for Eucalyptus species relating dbh to volume

S. No	Species	State	Equation	a	b	c	R^2	DBH	Reference
1	*E. globulus*	Tamilnadu	$(\text{Volume})_{overbark} = a + b*D$	-0.1219	0.034433	-	0.97	6-30	Jain *et al.*, 1993(a)[80]
2	*E. hybrid*	Uttar Pradesh	$(\text{Volume})_{overbark} = a + b*D + c*D^2$	-0.0208	0.006597	0.0009	0.96	9-39	Singh *et al.*, 1995[179]
3	*E. hybrid*	Uttar Pradesh	$(\text{Volume})_{overbark} = a + b*D^2$	-0.0903	0.000801	-	0.96	9-39	Singh *et al.*, 1995[179]
4	*E. camaldulensis*	Uttranchal	$V = a + b*D^2$	-0.0461	0.000874	-	0.97	6-30	Jain *et al.*, 1993(b)[81]
5	*E .camaldulensis*	Rajasthan	$\sqrt{(Twob)} = a + b*D$	-0.1188	0.031077	-	0.98	-	Tewari *et al.*, 2001[205]
6	*E. species*	Punjab	$\sqrt{V} = a + b*DBH$	-0.1545	0.035370	-	0.97	7-32	Jain *et al.*, 1991[79]
7	*E. hybrid*	Punjab	$\sqrt{V} = a + b*DBH$	-0.2297	0.03417		0.89	14-26	Jain *et al.*, 1991[79]
8	*E. hybrid*	Punjab	$\sqrt{V} = a + b*DBH$	-0.3015	0.04032		0.90	10-16	Jain *et al.*, 1991[79]
9	*E. hybrid*	Punjab	$\sqrt{V} = a + b*DBH$	-0.2582	0.03606		0.96	10-32	Jain *et al.*, 1991[79]
10	*E. hybrid*	Punjab	$\sqrt{V} = a + b*DBH$	-0.3670	0.04013		0.67	24-32	Jain *et al.*, 1991[79]
11	*E. hybrid*	Punjab	$\text{Log } V = a + b*\text{Log } D$	Raw dataset		-	-	7.1-43.9	Dogra and Sharma, 2003[47]
12	*E. hybrid*	Uttranchal	$\sqrt{V} = a + b*DBH$	-0.084	2.511	-	0.99	10-40	Chaturvedi and Khanna, 1982[36]
13	*E.species*	Uttranchal	$\sqrt{V} = a + b*DBH$	-0.0868	2.8335	-	0.99	10-40	Prasad, 1984[147]
14	*E. camaldulensis*	Rajasthan	$V = a * D^b$	0.00016	2.412	-	0.99	5-52	Tewari and Kumar, 2003(b)[204]

Table -2: Site-specific published equations in India Eucalyptus species relating dbh to above ground biomass

S. No	Species	State	Equation	a	b	R^2	DBH	Reference
1	*E. tereticornis*	Uttar Pradesh	$Y = a + b*(DBH)$	-149.08	15.99	0.80	1-40	Ajit *et al.*, 2006[6]
2	*E. tereticornis*	Uttar Pradesh	$Y = a + b*(DBH)$	-376.31	28.05	0.60	1-40	Ajit *et al.*, 2006[6]
3	*E. tereticornis*	Uttar Pradesh	$Y = a * (DBH)^b$	0.26	2.17	0.70	1-40	Ajit *et al.*, 2006[6]
4	*E. tereticornis*	Uttar Pradesh	$Y = a * (DBH)^b$	0.42	1.96	0.82	1-40	Ajit *et al.*, 2006[6]
5	*E. hybrid*	Haryana	$Y = a*(DBH)^b$	0.14	2.41	0.97	3.3-21	Tandon *et al.*, 1993[198]
6	*E. longana*	Karnataka	$Y = a + b*(DBH)$	-635.41	55.78	0.95	3-42	Rai, 1984 (a) [149]
7	*E. globulus*	Tamil nadu	Raw data					Negi and Sharma, 1987[132]
8	*E. tereticornis*	Karnataka	Raw data					Kushalappa, 1984[99]

6.4 Results and Discussions

6.4.1 Volume simulation

The simulated data set, covering the pseudo generated harvested data pertaining to five states (Uttar Pradesh, Tamil Nadu, Uttranchal, Punjab, Rajasthan), was generated from the site specific equations (secondary data) listed in Table-1. Additionally, a primary data set (Ajit *et al.*, 2000c[4]) consisting of thirteen harvested Eucalyptus trees was also included in the simulated data set. The dbh and tree wise volume ranged from 5.1 to 52.2 cm and 0.0078 to 2.203 m^3/tree respectively (Table-3) in the simulated dataset. Perfect normality was observed for volume, whereas dbh was approximately normally distributed (sw. p. value=0.10). The parameter estimates along with other related statistics, for the generalized equation relating volume to dbh, has been compiled in Table-4. The fitted generalized allometric equation (Fig. 1) is

$$Y = 0.00093*(X)^{1.96} \quad \text{..................(1)}$$

where Y= volume (m^3/tree) and X=dbh (cm).

Fig.4. depicts a case by case comparison of observed values generated from the site specific allometric equations, predicted values from the derived generalized allometric equation (i.e. Eq. (1)), and the raw residuals. Positive raw residuals indicate over prediction by the generalized allometric equation whereas negative raw residuals indicate under prediction by the generalized allometric equation (Fig. 4). The relatively small residual values depicted in Fig. 4 confirms the appropriateness and utility of generalized allometric equation to predict the volume of standing Eucalyptus trees over a very wide range of spatial (location) and temporal (age) range.

The validation dataset, used for validation of the generalized volume equations, pertains to sequential harvesting of trees (tissue culture raised clones obtained from Tata Energy Research Institute, New Delhi) from a designed experiment conducted at NRCAF, Jhansi encompassing a dbh range of 4.05 to 9.30 cm and volume of 0.0033 to 0.0335 m^3/tree (Table-5) with perfect normality of both tree variate i.e dbh and volume (sw. p values < 0.04).

The residuals (defined as the difference of predicted values from generalized regression and observed values in the validation data set) were distributed normally with a mean volume values of 0.00205 m^3/tree (Table-6). The validation of the model was further strengthened by fitting a linear equation (predicted values= a+b* observed values) between the predicted and observed values (Fig. 2). For a perfect fit model the 'a' value should approach to 'zero' and 'b' value should approach to 'one' with a perfect unity R^2- values. In this case, the value of 'a' was observed to 0.00685 and 'b' as 0.564 with R^2- value of 0.91(Table-7). The error of prediction, termed as residual, is computed as the difference in the observed and predicted values. Theoretically, the residual should be independently and normally distributed with mean zero and constant variance. These assumptions were evaluated through pertinent graphs (Fig. 3). The plots of residuals against the explanatory variate (dbh) ensures that the residuals are not being continuously over or under estimated. The strong agreement between the derived generalized allometric equation and validation with new data set is further sustained by low mean absolute error of 0.00414 m^3/tree.

Table-3: Summary characteristics of growth attributes for volume-dbh simulated dataset.

Measured variable	No. of Cases	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	*SW Statistic	SW P-Value
Dbh	112	23.74 (5.1-52.2)	9.642	0.1475 (0.2284)	-0.5263 (0.4530)	0.9807	0.10693
Volume	112	0.548 (0.00780-2.203)	0.421	0.93849 (0.22843)	1.13038 (0.45309)	0.93226	0.00003

*SW- Shaphiro wilk's statistic for normality testing

Table- 4: Allometric model fitted on the volume-dbh simulated dataset.

Parameters	Estimate Value	Standard Error	Confidence Interval		R^2
			Minimum	Maximum	
a	0.00093	0.00027	0.00038	0.00147	
b	1.96	0.0837	1.8024	2.13449	0.87

Table-5: Summary Characteristics of growth attributes for the independent validation dataset.

Measured variable	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
Dbh	7.23 (4.05-9.30)	1.54	-0.573 (0.564)	-0.562 (1.090)	0.948	0.0461
Volume	0.020 (0.0033-0..0335)	0.00955	-0.598 (0.564)	-.0837 (1.090)	0.918	0.0161

Table-6: Descriptive statistics of residuals for the volume-dbh generalized regression equation.

Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
0.00205 (-0.00541-0.00833)	0.00446	-0.4138 (0.564)	-0.9779 (1.090)	0.935	0.029733

Table-7: Validation of allometric model on new independent dataset by fitting a linear equation between predicted and observed volume values (predicted volume=a+b*observed volume).

Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
			Lower	Upper	
a	0.00685	0.0010	0.00467	0.00903	0.91
b	0.564	0.0452	0.4677	0.66186	

Fig. 1. Points generated from individual regressions for Eucalyptus volume pertaining to various states of India and the resulting generalized volume regression line.

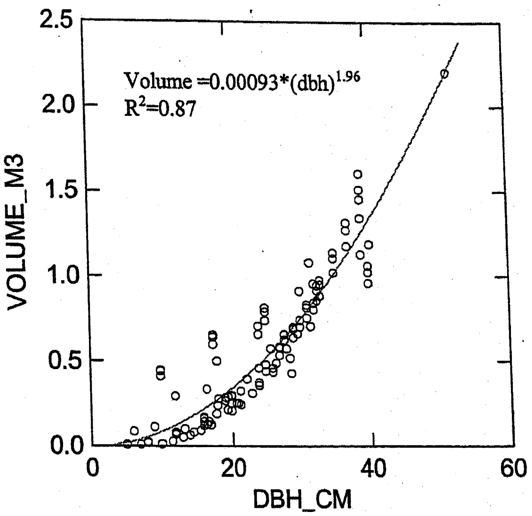


Fig. 2. Graphs of the linear function fitted between the predicted and observed values (predicted volume= a+b*observed volume) for Eucalyptus species in India. (For a perfect model, 'a' should be zero and 'b' should be unity along with absolute one R^2-value).

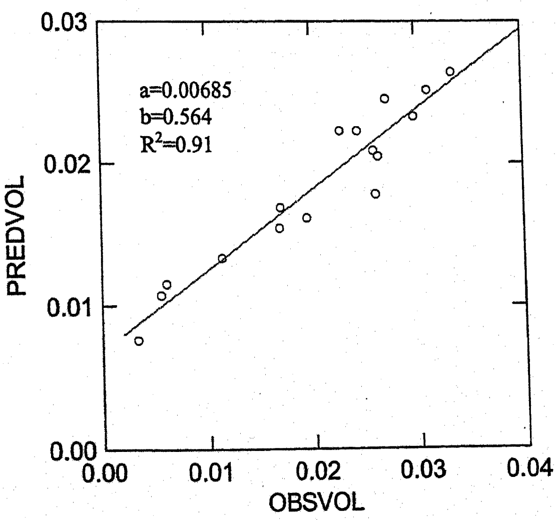


Fig. 3: Various plots of residual diagnostics on the validation dataset for the generalized volume regression allometric function.

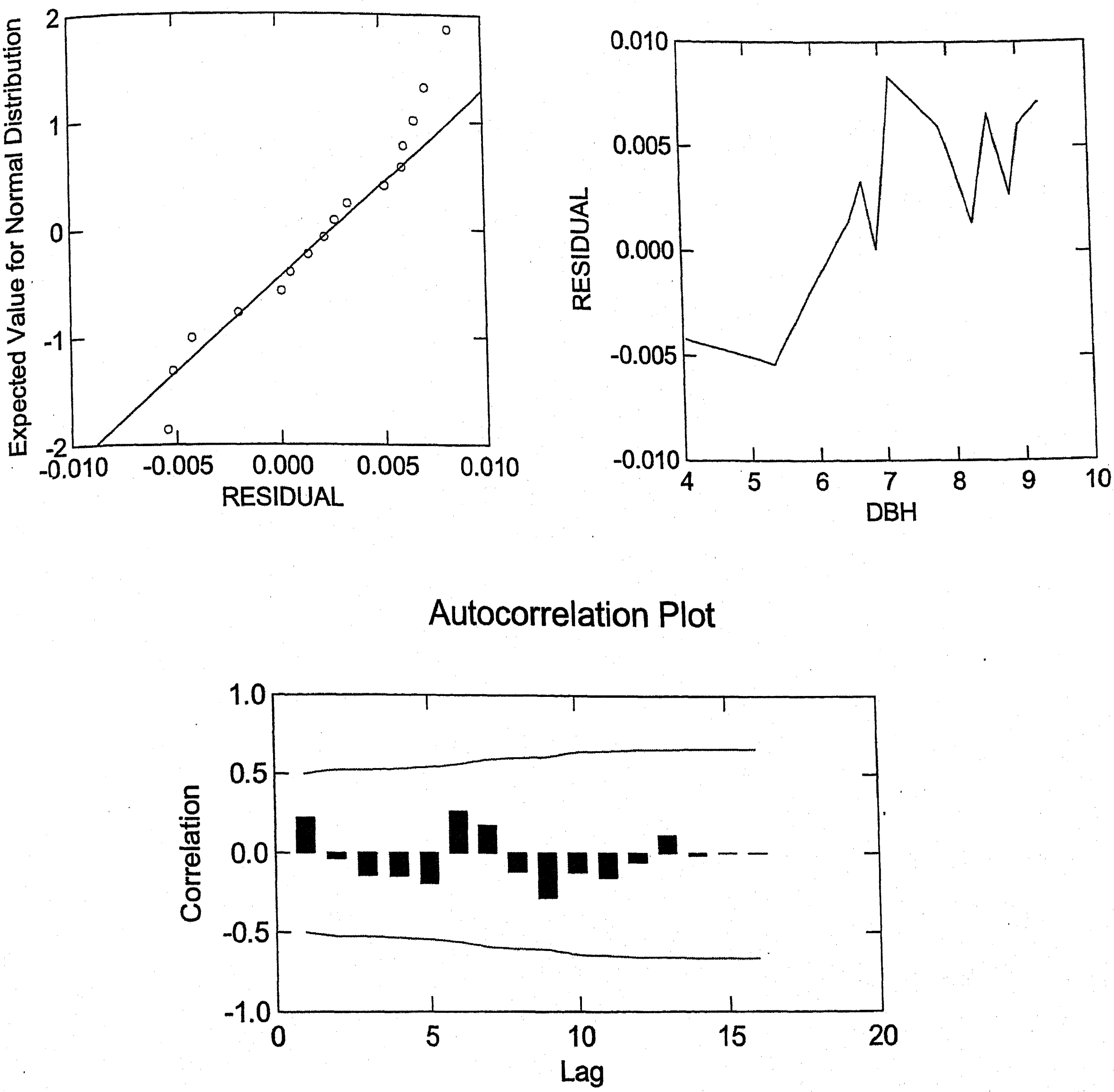
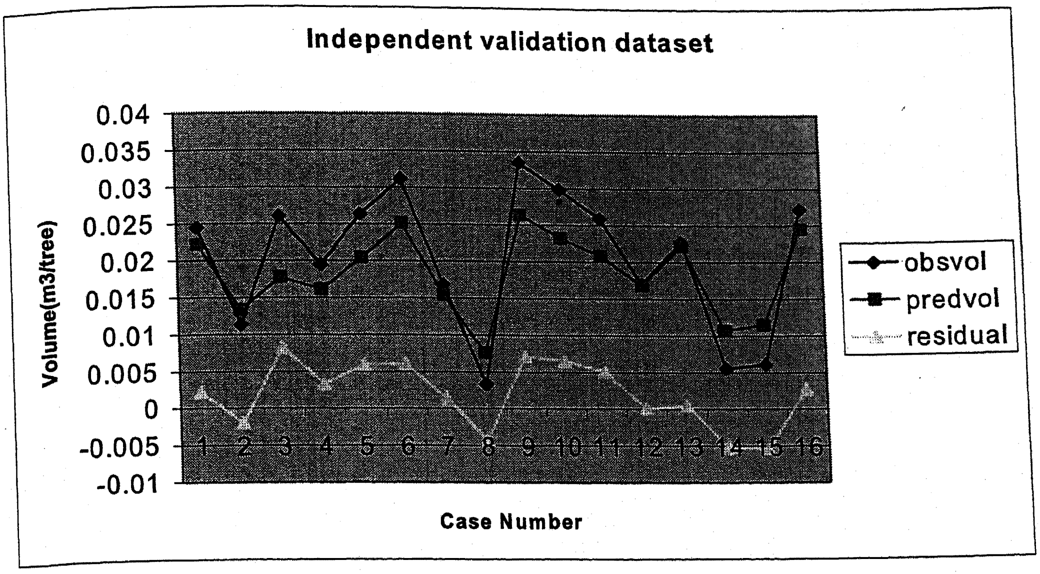


Fig. 4: Case wise plot of the predicted and observed values with raw residuals pertaining to the validation dataset, for volume-dbh generalized equation.



6.4.2 Above Ground Biomass simulation

The simulated data set was generated from the site specific equations covering four states namely Uttar Pradesh, Haryana, Karnataka and Tamil Nadu as listed in Table-2. Additionally, a primary data set (Negi and Sharma, 1987[132]; Kushalappa, 1984[99]) consisting of total fifteen harvested Eucalyptus trees was also included in the simulated data set. The dbh and tree wise aboveground biomass (AGB) ranged from 1 to 42 cm and 0.260 to 778.83 kg/tree respectively (Table-8) in the simulated dataset. Perfect normality was observed for biomass, and dbh (sw. p values < 0.00). The parameter estimates along with other related statistics for the generalized equation relating AGB to dbh, has been compiled in Table-9. The fitted generalized allometric equation (Fig. 5) is

$Y= 0.74*(X)^{1.81}$ ....(2)

where Y= Aboveground Biomass (kg/tree) and X=dbh (cm).

Fig. 8 depicts a case by case comparison of observed values generated from the site specific allometric equations, predicted values from the derived generalized allometric equation (i.e. Eq. (2), and the raw residuals. Positive raw residuals indicate over prediction by the generalized allometric equation whereas negative raw residuals indicate under prediction by the generalized allometric equation. The relatively small residuals values depicted in Fig. 8 confirms the appropriateness and utility of generalized allometric equation to predict the aboveground biomass of standing Eucalyptus trees over a very wide range of spatial (location) and temporal (age) range.

The validation of the model was performed using an independent data set (pertaining to an experiment on MPTs for energy and boundary plantation conducted at NRCAF,

Jhansi) of harvested trees encompassing a dbh range of 9.55 to 26.11 cm and biomass of 39.30 to 275.92 kg/tree (Table-10) with normality of both tree variates viz dbh and AGB (sw. p values < 0.06).

The residuals were distributed normally with a mean values of –1.00 kg/tree (Table-11). The plots of residuals against the explanatory variate (dbh) ensures that the residuals are not being continuously over or under estimated (Fig. 7). The validation of the model was further strengthened by fitting a linear equation (predicted values= a+b* observed values) between the predicted and observed values (Fig. 6). For a perfect fit model the 'a' value should approach to 'zero' and 'b' value should approach to 'one' with a perfect unity R^2- values. In this case, the value of 'a' was observed to be 3.17 and 'b' as 0.98 with R^2- value of 0.98 (Table-12). Although, the positive values of 'a' as 3.17 indicate slight over estimation by the derived generalized biomass equation. However, if we convert this absolute residual values to relative residual value:

Relative residual value= (absolute residual/observed biomass)*100

These values (relative residuals) are less than 2% indicating there by the prediction errors are relatively very small and thus the derived generalized equations can be used with a accuracy prediction level of 98% or more. The strong agreement between the derived generalized allometric equation and validation with new data set is further sustained by low mean absolute error of 6.348 kg/tree.

While site-specific allometric equations are likely the best method to calculate biomass/ volume, the destructive sampling necessary to derive them is prohibitive in terms of time and expense. Logic dictates that the application of site-specific allometric equations to sites where they were not developed would not be prudent. Thus, the generalized allometric equation derived and validated in this study may be

used with confidence by foresters, forest ecologists, and other scientists seeking estimates and predictions of volume and aboveground biomass for Eucalyptus in India.

Table-8: Summary characteristics of growth attributes for ABG-dbh simulated dataset.

Measured variable	No. of Cases	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	*SW Statistic	SW P-Value
Dbh	55	17.47 (1.00-42.00)	10.33	0.8537 (0.3217)	0.2313 (0.6335)	0.9161	0.00096
AGB	55	163.63 (0.260-778.83)	182.98	1.7796 (0.32174)	2.9267 (0.6335)	0.7829	0.00000

*SW- Shaphiro wilk's statistic for normality testing

Table- 9: Allometric model fitted on the ABG-dbh simulated dataset

Parameters	Estimate Value	Standard Error	Confidence Interval		R^2
			Minimum	Maximum	
a	0.74	0.255	0.2291	1.252	
b	1.81	0.098	1.617	2.011	0.91

Table-10: Summary Characteristics of growth attributes for the independent validation dataset

Measured variable	Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
Dbh	19.52 (9.55-26.11)	4.73	-0.389 (0.512)	-0.388 (0.9923)	0.9513	0.03882
AGB	165.96 (39.30-275.92)	68.61	0.0039 (0.512)	-0.747 (0.9923)	0.966	0.0671

Table-11: Descriptive statistics of residuals for the ABG-dbh generalized regression equation.

Average (Min, Max.)	Standard Deviation	Skewness (SE of Skewness)	Kurtosis (SE of Kurtosis)	SW Statistic	SW P-Value
-1.00 (-12.60-9.76)	7.196	0.130 (0.512)	-1.359 (0.9923)	0.9333	0.01792

Table-12: Validation of allometric model on new independent dataset by fitting a linear equation between predicted and observed ABG values (predicted ABG=a+b*observed ABG).

Parameter	Estimate	Asymptotic Standard Error	Wald Confidence Interval 95%		R^2
			Lower	Upper	
a	3.17	4.388	-6.04	12.39	0.98
b	0.98	0.024	0.935	1.03	

Fig. 5: Points generated from individual regressions for Eucalyptus and the resulting generalized regression line.

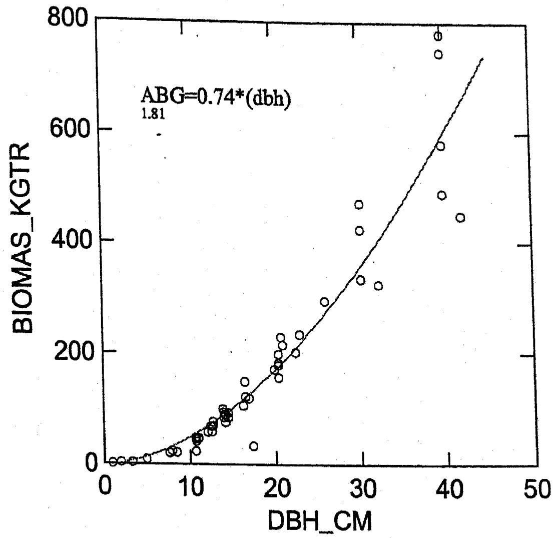


Fig. 6: Graphs of the linear function fitted between the predicted and observed values (predicted biomass= a+b*observed biomass) for Eucalyptus species in India. (For a perfect model, 'a' should be zero and 'b' should be unity along with absolute one R^2-value).

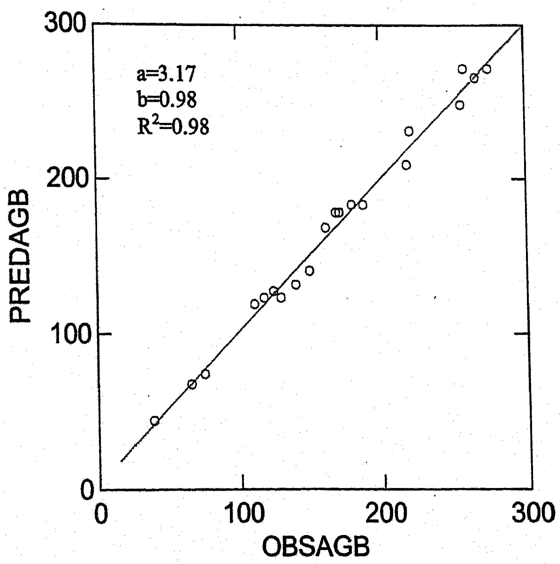
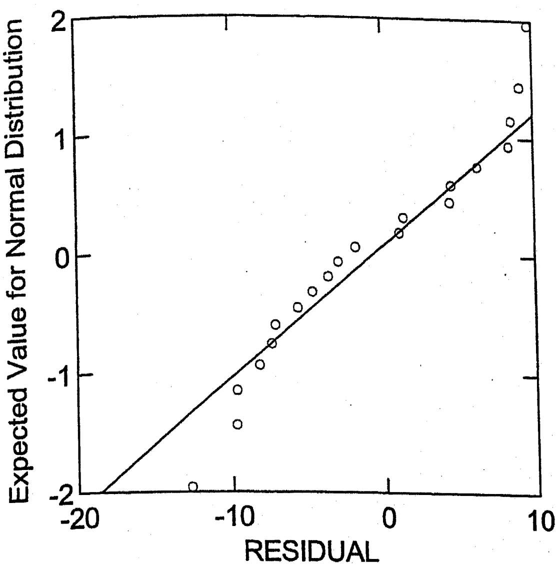
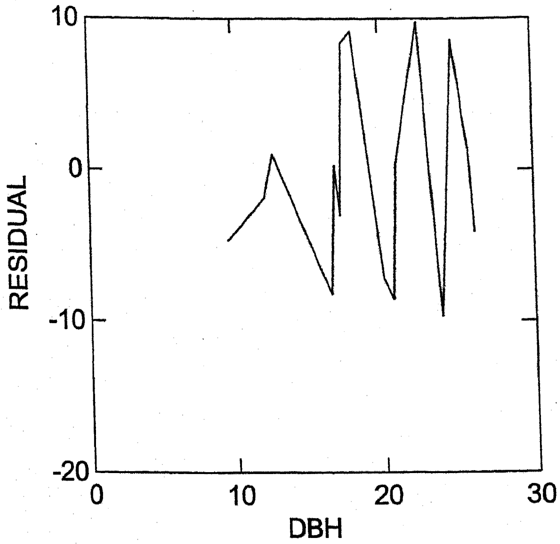


Fig. 7: Various plots of residual diagnostics on the aboveground biomass validation dataset for the allometric function.





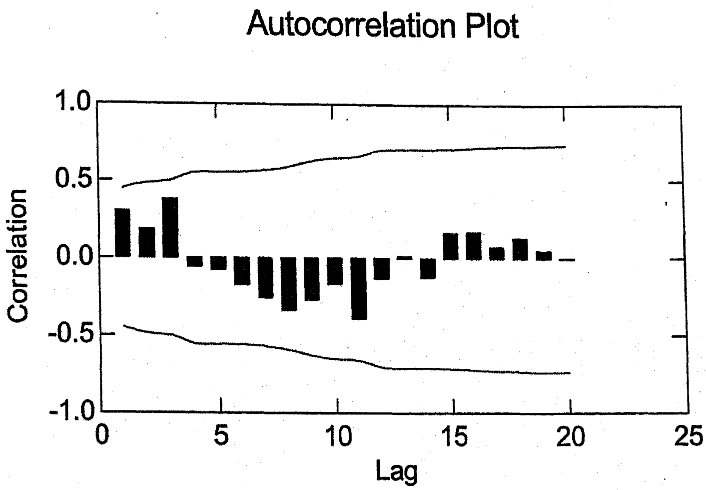
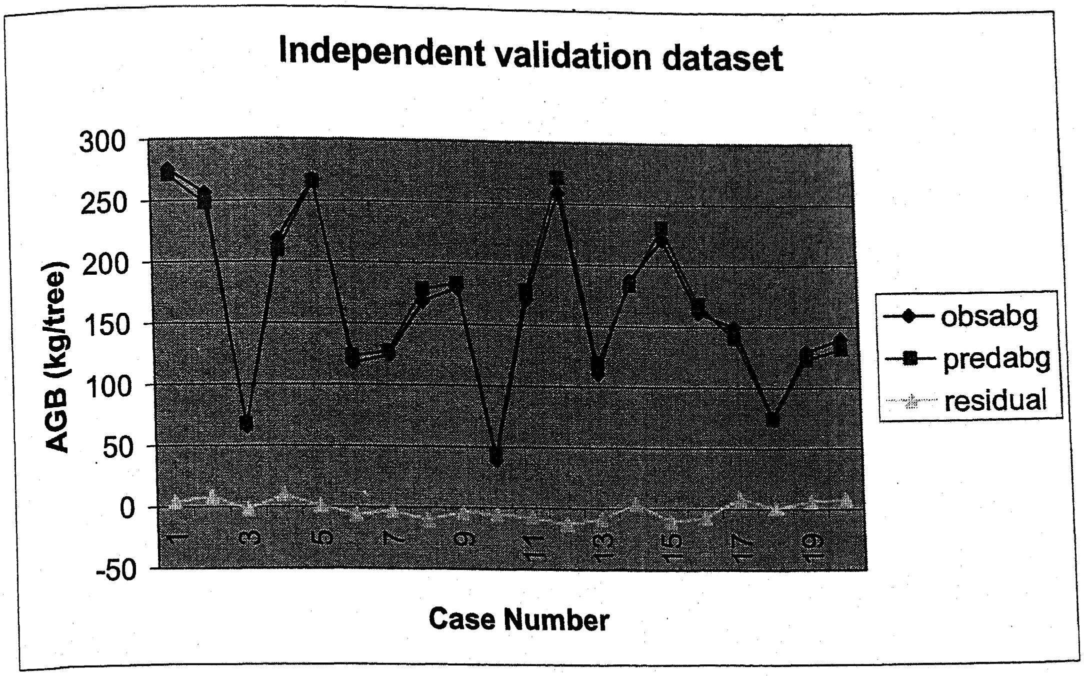


Fig. 8: Case wise plot of the predicted and observed values with raw residuals for ABG-dbh generalized equation.



Chapter-7

Development of Tree Growth Modelling Website in Indian Perspective and its launching on World Wide Web

Development of Tree Growth Modelling Website in Indian Perspective and its launching on World Wide Web.

7.1 Introduction

The present era has seen an exponential growth and diversification in all forms of information, which is sometimes called, as information explosion. It has been made possible due to the impact of computer technology on the modern society. Computerized information systems have influenced nearly all types of organizations, whether small or large, public or private, national or multinational. Information systems viz (decision support system, expert system etc.) exist for almost all the fields. Information systems are concerned with data capture, storage, analysis and retrieval. In the context of agricultural in general and agroforestry in particular, they are vital to assist decision making in a short time frame, potentially allowing decisions to be made and practices to be auctioned in real time. There are many tree species which have been recommended to be adopted in agroforestry systems, prominent among them are Eucalyptus, Poplar, *Casurina equisitifolia*, Prosopis, etc. Eucalyptus species has been widely accepted by the farmers not only in pure plantations but also even with more enthusiasm along with crops i.e. in agroforestry because of its short rotation cycle, rapid growth and excellent fibre qualities. Eucalyptus species has also been recommended as among the six tree species to be used for agroforestry in India identified by the Planning Commission through its "Task Force on Greening India" that published its report in June, 2001. With the increased recognition of fast growing tree species as an alternative to wood production, many scientists and development workers have focused their interest on short rotation tree species. However, this rapidly rising interest is not matched by a corresponding level of available information, which is crucial to their proper assessment, evaluation and use in agroforestry research and development.

Consequently the task of systematic collection, storage, evaluation and dissemination of information on fast growing tree species calls for attention as a matter of urgency. As one of the major problems, peculiar to these species, is the process of data collection and management. Attention is drawn to the need to facilitate dissemination of this information. DBMS (Database Management System) is one such tool, which is invariably used in almost all displines of forestry/agroforestry and agriculture for dissemenation of information through world wide web (Ajit *et al.*, 2004[5]). A database provides a computer platform for tabulation, storage and retrieval of huge information and with the rapid development of computers and Internet, it is now possible to access the databases globally which has resulted into availability of information at fingertip (Ajit *et al.*, 2005[7]). Some databases on forestry and related aspects has been developed abroad. Landis *et al.,* (1999)[106] developed Global Forest Information Service (GFIS) under the auspices of the International Union of Forest Research Organizations (IUFRO) to provide worldwide access to forest information. 'MPTSys' - a software on multipurpose tree species (Venkateswarlu, 1994)[217], which is a user-friendly microcomputer software package has been designed to help scientists, administrators and extension workers to organize, manage and share research information on multipurpose trees. EUCALIST and TREDAT, developed at CSIRO Division of Forestry and Forest Products, Australia, contains more than 100000 records on the natural occurrence of Eucalyptus in Australia (Brown, 1989) [22]. IADSS-Information and Decision Support System: a user friendly software package was designed to help scientists for managing field research data and other information on multipurpose trees and their potential for producing fuelwood and other products (Cady *et al.*, 1989)[26]. Carlowitz (1989)[28] at ICRAF led the team responsible for establishing the MPTS database. MPTS database of ICRAF was intended to be used as a decision support tool for selection of agroforestry tree species (Schroder and Jaenicke, 1994)[174]. It was further revised,

refined, modified and renamed as the Agroforestree database (AFT) and released as a stand alone application on CD-ROM (Salim *et al.*, 1998)[169]. Rose (1989)[168] expressed the serious concern over the need and expected benefits from global databases and research networking, with particular reference to growth models of MPTS in the tropics. Moreover, databases experiences in tropical forestry are also outlined with respect to work done by CATIE (the MIRA database).

Hann, 2004[69] developed ORGANON, an individual tree growth model for Douglas-fir and western hemlock that uses a list of trees, each with exact measurements, as input data. The user can specify periods of growth, in five year increments, and management such as thinning, fertilizing, and pruning. The program produces stand statistics at each step, and yield tables after final harvest of the stand.

Kitchen, 2008[92] highlighted examples of spatial information collection and processing to accomplish real- or near real-time management operations in precision agriculture.

Ellis *et al.*, 2005[52] developed SEADSS (Southeastern Agroforestry Decision Support System), a web-based application to assist landowners and extension agents in the Southeast United States to evaluate potential sites and suitable tree and shrub species for agroforestry planning.

Ellis and Schoeneberger, 2004[53] highlighted the application of different Computer-based Decision Support Tools (DST) like databases, geographical information system, models, knowledge-base or expert systems, and 'hybrid' decision support systems in agroforestry research and development.

Food and Agricultural organization (FAO, 2007)[55] has developed database on tropical forages that contains description of more than 600 grassland species and a linked picture gallery of photos.

Infact, the work on development of databases on agroforestry in India was initiated by this team itself. Moreover, development of an exclusive site dedicated to tree Growth Modelling in India, was initiated as one of the objectives of this thesis work itself. This website is probably, the first of its kind in India. An attempt has been made in this study to provide maximum possible information on tree growth modeling in general and eucalyptus modelling in a holistic manner. However, no such databases could be traced in India related to forestry and agroforestry. This website will not only help to avoid duplication of efforts on modelling but also provide a single platform, where all published information on Eucalyptus modelling in India would be available at stretch, with an in depth pros and cons.

7.2 Materials and methods

Secondary data/information on eucalyptus species has been collected, evaluated and synthesized freely from the published information available in the form of journals, books, bulletins, reports, newsletters, articles, leaflets etc. from the 38 centers of All India Coordinated Research Project on Agroforestry and ICAR institutes like NRCAF, IGFRI, CRIDA, CAZRI, CARI, CSSRI, etc and ICFRE institutes/ NGO's etc. The information was compiled, collated and fed into the database. HTML and DHTML have been used for creating the dynamic pages of the database at the front end. ***Tree gowth modelling website*** is a compilation of a biomass and volume equations pertaining to eucalyptus published in Indian Context. This website has been hosted at the server of Indian Agricultural Statistics Research Institute (IASRI), New Delhi and these dynamic web pages are fully functional and one can visit at URL

http://mirror.iasri.res.in/net/tgm/index.html. to view, browse and download information on the subject.

7.3 Results and Discussions

This site entitled "Tree Growth Modelling: Indian Experiences" has been designed with the basic objective of providing a platform where the user can have the basic concepts used in development of tree growth models at one end and the comprehensive collection of already developed model for a specific tree species at other end so as to use them directly for prediction purposes. There are a number of fast growing tree species like Eucalyptus, Poplus etc. that have been widely accepted by the Indian farmers in agroforestry/block plantations. The basic reason for adoption being the short rotation nature, which provides farmers substantial returns at early age. Keeping these considerations in mind, at the initial phase of development of this site, we have concentrated on Eucalyptus species modelling. This site is a unique collection of published biomass and volume equations, on Eucalyptus, off course, in Indian context only. At this stage, as per the objectives of this thesis, we have concentrated on eucalyptus only. However, other species adopted for agroforestry in India viz Poplar, Casurina, Prosopis, Albizzia etc. will be added in near future.

The general portion of this site describes **definition of modelling** by various authors and principles of modeling (Fig. 2); **types of modelling** describing about various types of models like descriptive models, prescriptive models, predictive models and simulation models (Fig. 3); **model development process** depicting various steps of model development process like model estimation and model validation (Fig. 4); **tree growth modelling techniques** describes essential steps of modelling tree growth like sampling of trees, measurement of height, diameter measurement, volume computation, height measurement, estimation of biomass components etc. (Fig. 5);

models relevant to agroforestry provides the working outlines of the models relevant to agroforestry worldwide (Fig. 6); and finally we have added **tree growth modelling publication** displaying a compilation of publication (of our team at NRCAF) on tree growth modeling along with full length papers available in pdf format for downloading (Fig. 7).

At present stage we have concentrated only on eucalyptus species as per objective of this thesis, Accordingly, in this site under Eucalyptus introduction (Fig. 8); one can find general introduction of eucalyptus and its common uses and importance; Further more we have added published biomass equation in India (Fig. 9), like wise published volume equations in India along with abstracts (Fig. 10), and lastly a photo gallery displaying few snapshots of ongoing Eucalyptus trials at the Central Research Farm of NRCAF, Jhansi (Fig. 11).

This "Tree Growth Modelling website" has been designed to help for organizing, managing and sharing research information Eucalyptus modelling in India. HTML, DHTML have been used for creating the dynamic pages of the database at the front end and the source codes written in HTML for designing the home page of Tree Growth Modeling Web site has been appended in Annexure I. The software works on a HTTP Server and cater the requirement of client that may on any computer connected with Internet and having a graphic web browser. The unified database has been equipped with interactive web pages to browse information on Eucalytus introduction, modelling introduction, types of modelling, model development process, detailed information on biomass and volume models in India related to Eucalyptus species.

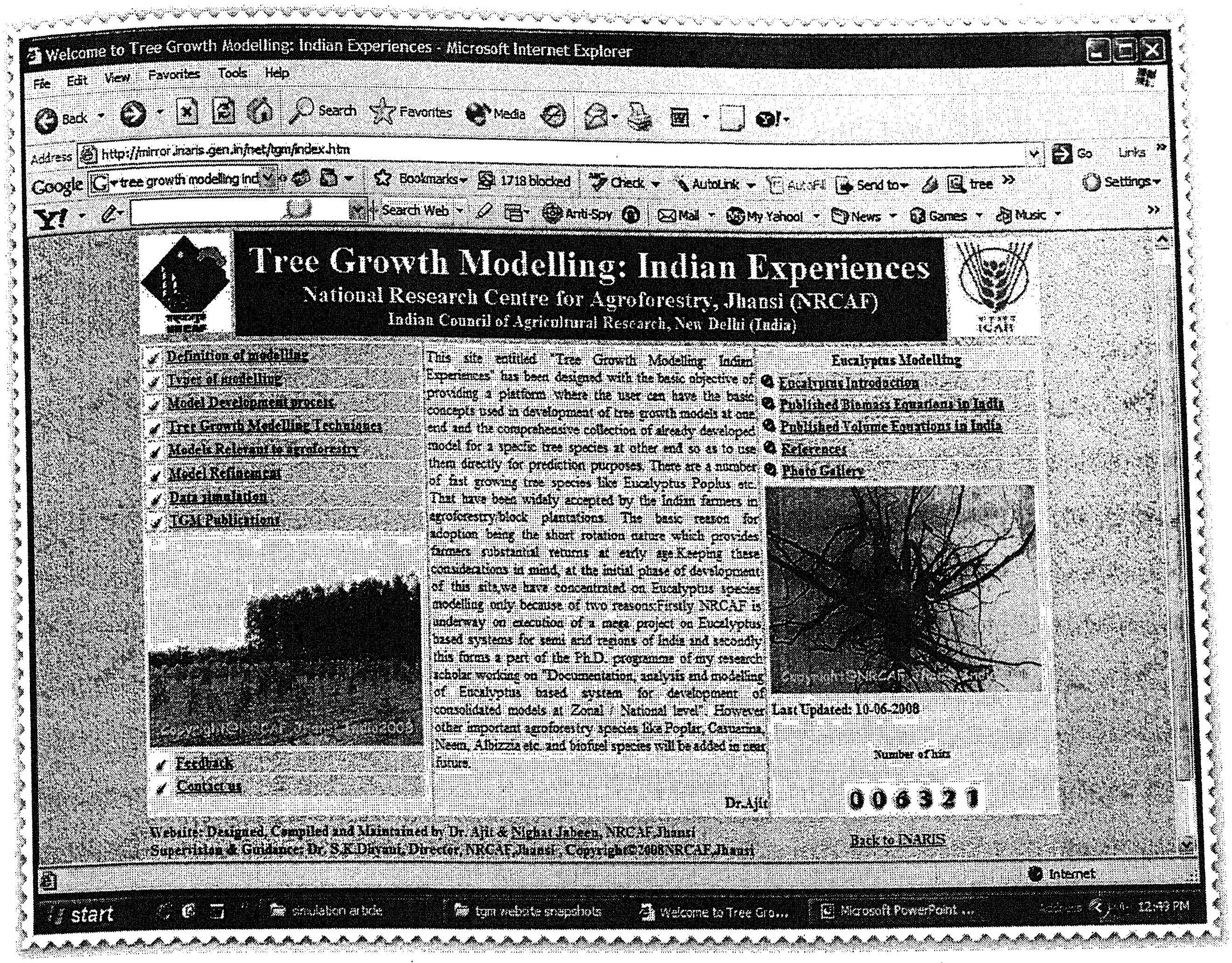


Fig. 1: Home page of Tree Growth Modelling Website

http://mirror.iasri.res.in/net/tgm/index.htm

Modelling

Various researchers have defined modelling in their own way, some prominent and worth mentioning are:

Mclone and Andersons (1976)[16] described modelling as the representation of our so called 'real-world' in mathematical terms so that we may gain a more precise understanding of its significant properties, and which may hopefully allow some form of prediction of future events.

Hall (1963)[12] has said "The goal of modelling is to understand reality mathematically".

Meyer (1985)[18] defined model to be an object or concept that is used to represent something else. It is reality scaled down and converted to a form we can comprehend. He further adds that a mathematical model is a model whose parts are mathematical concepts, such as constants, variables, functions, equations, inequalities, etc.

Modeling has been used in natural sciences since centuries in one way or the other. However, system modelling as a discipline in itself established in the current century only. Models have been built in the physical, biological and social sciences. The building blocks for these models have been taken from calculus, algebra, statistics, geometry, probability and nearly every other field within mathematics.

Agroforestry modelling is a complex process that essentially involves at least two elements viz tree and crop, where tree is the long term and crop is the short term component. Agroforestry models, usually, predict tree growth and yield and the reduction/enhancement in crop yield as influenced by the tree component in temporal and spatial sequence. Models providing the most accurate prediction of height included basal area, trees/ ha, dominant stand height, and diameter at breast height (DBH)(Sharma and Parton,2007[25]).

Growth of the tree results from two opposing factors: firstly the positive component associated with biotic potential, photosynthesis activity, absorption of nutrients, constructive metabolism etc., and secondly the negative component representing the restraints imposed by competition, limited resources, stress, respiration and aging factors. These two components when combined together results in the sigmoid shape of tree growth

Fig. 2: Various definitions

Types of Modelling

Agroforestry models can be classified in many ways. There is frequently some degree of overlap and fuzziness between the different classifications, and between the classes within one classification. Attempts to classify models frequently confuse as much as they clarify. It is, perhaps, more useful to think of model classification in relation to pure examples of each class, with many models sharing the attributes of more than one class, rather than to expect that the classification will result in a clear-cut partitioning of all models into discrete groups. One useful classification, proposed by Davey *et al.*, (1991)[6] is into descriptive, prescriptive and predictive type of model.

1.1 Descriptive Models

Descriptive models are primarily intended for structuring and communicating knowledge about the system. Clearly, the main function of this type of models is to describe the system. However, one could conceivably use even this type of information for making inferences: for example, on the changes that one might expect over some short period of time, or on the relative susceptibility of two such systems to disturbance.

1.2 Prescriptive Models

Prescriptive models are primarily intended for inferring what action a manager of the system should take under given conditions, in order to achieve some goal. In other words, the role of prescriptive model is to generate a set of management recommendations given a goal and a set of values characterizing a given system. The management recommendations relate to the decisions that a manager can take. They may be quantitative (e.g. spacing between crop rows, amount of mulch to apply or time to prune the lower branches of trees), or they may be qualitative (e.g. species of hedge to plant in an alley cropping system or type of erosion control method to apply) various forms of prescriptive models are as follows:

- **Prescriptive equations**

These consists of an equation (or a set of equations) whose inputs are site conditions and whose output is a management variable. Prescriptive equation models generally have no explanatory component. However, they may be derived mathematically from a mechanistically-based or theoretical model, as in optimum harvesting models. The goal is usually implicit (for example, to maximize crop yield) rather than an explicit input to

Fig. 3: Types of models

Model Development Process

Development of a model, essentially involves two stages

- Model ESTIMATION
- Model VALIDATION

Construction of a precise model, not only includes sound mathematical /statistical formulation based on theoretical considerations of the process being modelled but equally important are practical observations and from this view point, it is desirable that one should have two independent data sets, one to be used for model estimation and the other for model validation. However, if the practical situations does not permit to have two independent data sets, then the single data set should be judiciously utilized for model estimation and validation. Geisser (1975)[1] suggested that out of a single data set, a random sample (with out replacement) of about 80% data points should be selected and it should be utilized for model estimation and the remaining 20% data points may be kept as the second independent data set to be used for model validation.

1.2.1 Model Estimation

At this stage the model is formally developed on the basis of theoretical considerations and experimental observations. Model estimation involves three steps;

Simplification or idealization

It includes translation of a real life situation into a problem amenable to mathematical treatment. This is a crucial stage since the real situation is usually complex, involving many processes. Some features will appear significant, many others irrelevant. This stage essentially involves variable identification. A major decision often taken at the very onset of modelling concerns the nature of mathematical variables involved. Basically

Fig. 4: Working details of model development process

Tree Growth Modelling Techniques

Tree being a perennial component has to be retained for longer durations in farm lands(whether in sole plantation or with intercrops).The researchers/managers/policy makers are generally interested in prediction of biomass/ volume of standing trees on the basis of easily measurable growth variables like dbh(diameter at breast height). Tree growth models are such mathematical/statistical tools that may provide reliable estimates of volume/ biomass components at any stage/ age.It is therefore, required to either develop such models (by harvesting trees)or use already developed models for prediction of tree growth/yield.

The basic techniques start with the sampling of trees that represents the tree population in a system, then the harvesting of trees and finally the recording of observations on the harvested trees. Some of the basics of tree data recording are discussed below.

Sampling of trees :

The most accurate method of assessment of biomass can be the complete harvest, however cutting and weighing every tree is not possible. Sampling of trees is necessary to avoid such difficulties. In laying out an agroforestry experiment it should be ascertain that at the end of experimental period the number of trees per treatment would be 9-12 for single site. This is the minimum number, we may select more when trees are clearly variable due to soil variability etc. Tree can be selected with stratification by size to ensure the whole size range is covered. Although random sampling is easier to do than using recommended stratified sampling. The random method is potentially dangerous, because the selected trees may not cover the whole range. When using random sampling, we may take minimum 16 trees as sample per treatment. For tree selection, we rank all the trees according to CD (collar diameter) in descending order and delete the smallest tree (s) from list until remaining number of trees are divisible by 3 (i.e. if there are 17 trees in the plot, we should take larger 15 and divide them into tree groups. Within each group, randomly select 1,2,3 trees as per the minimum number of tree required for each treatment. All the trees should be cut 20 cm above the ground.

Measurement of height :

In forestry concept, surveyor can measure the approximate height of a standing tree with a transit, but in case of destructive sampling when a tree

Fig. 5: Techniques of "Tree Growth Modelling" and harvest data recording

Models Relevant to Agroforestry

Agroforestry is an interdisciplinary subject area within which many models and modelling paradigms are relevant and have been applied, creating problems in attempting to review relevant models. There are large number of modelling paradigms within which the models are constructed. Steppler and Raintree (1988)[24] emphasize the importance of paradigms for the development of agroforestry, but also the dynamic nature of the rise, acceptance and fall of particular paradigms. In modelling, there is the additional problem of multiple paradigms, but the compartment flow-influence paradigms is dominant. However, there are many other such as those based on matrix algebra, probability theory, chaos, fractals or object-oriented programming.

There are many relevant models within a particular paradigm. This is especially true in agroforestry, with its links to many areas of ecology. Dale *et al.*, (1985)[5] refer to there being several hundreds single tree forest growth models, and there are probably greater number in other areas, such as crop growth and water dynamics.

It is clear from the preceding description that it would have been neither possible nor productive to calculate all models relevant to agroforestry and so the approach has been to summarize the models along with modelling approaches that have been adopted and characterizing the tasks involved in agroforestry modelling.

MAESTRO - Light interception by a tree within an array of trees (Wang and Jarvis, 1990)[26] may be used to predict absorption of radiation by a crown surrounded by the crowns of other trees. The inputs are site location, slope bearing, soil temperature, reflectance, leaf transmittances and reflectance, density distribution, physiological parameters, tree coordinates, crown dimensions. The outputs are radiation flux density at any point in the stand, hourly and daily amounts absorbed, photosynthesis and transpiration. The time base is hourly for one growing system. The model has been implemented as FORTRAN program.

SCUAF - Soil changes under agroforestry (Young and Mairya, 1991)[27]

Fig. 6: Models relevant to agroforestry research

Tree Growth Modelling Publications at NRCAF, Jhansi

1. **Ajit**, Ritu, **Nighat Jabeen**, Handa, A.K., Singh, R. and Chaturvedi, O.P. (2008). A regionalized growth model for Eucalyptus tereticornis plantations under semiarid Conditions of India . Indian Journal of Agroforestry. 10(1): **(Full text pdf)** In Press.

2. **Ajit**, Ritu, **Nighat Jabeen**, Handa, A.K. and Chaturvedi, O.P. (2008). Statistical prediction of height through height-diameter models for Eucalyptus tereticornis in central India . In Proceedings of National Symposium on Intensive Forest Farming: The State of the Art, held during Feb.12-14, 2008 at PAU , Ludhiana 146-147 pp. **(Full text pdf)**

3. **Ajit**, Handa, A.K. and Uma. (2007). Agroforestry Modelling. In: Agroforestry Systems and Practices (Eds. Sunil Puri and Pankaj Panwar). New India Publishing Agency, New Delhi pp 497-517. **(Full text pdf)**

4. **Ajit**, Rai, P., Handa, A.K. Chaudhari, S. and Uma. (2006). Allometry for estimating above ground biomass of E. tereticornis under energy and boundary plantations in central India . Annals of Arid Zone. 45(2):175-182. **(Full text pdf)**

5. **Ajit**, Ritu, Handa, A.K. and Chaturvedi, O.P. (2006). Model for estimation of root biomass in Eucalyptus tereticornis . Bhartiya Krishi Anusandhan Patrika 21 (2): 154-158. (In Hindi) **(Full text pdf)**

6. **Ajit**, Ritu, **Nighat Jabeen**, Singh, R., Handa, A.K, Ram Newaj and Chaturvedi, O.P. (2006). Comparison Of initial growth and yield of Eucalyptus tereticornis clones under agroforestry system vis a vis block plantations in semi-arid conditions of India . In Abstract of National Symposium on Agroforestry for livelihood security, environmental protection & biofuel production held at NRCAF, Jhansi during 16-18 Dec., 2006. 125-126 pp. **(Full text pdf)**

7. **Ajit**, Shrivastava, R., Chaturvedi, O.P., Handa, A.K., Ram Newaj and Dhyani, S.K. (2006). Estimation of missing root biomass for Eucalyptus tereticornis plantations in complete excavation studies under semi arid conditions in India . In Abstract of proceedings of International Conference on Statistics and Informatics in Agricultural Research held at Indian Agricultural Statistical Research Institute, New Delhi on 27-30 Dec., 2006 57-58pp. **(Full text pdf)**

Fig. 7: Tree growth modelling publications at NRCAF, Jhansi

Eucalyptus: Introduction

Eucalyptus tereticornis native to eastern Australia was introduced to India in 1919. It has a great many common names, of which Forest Red Gum is perhaps the most widely known. Other common names include Bastard Box , Blue Gum , Flooded Gum , Grey Gum , Mountain Gum , Queensland Blue Gum , Red Gum , Red Ironbark , Red Irongum and Slaty Gum. It has had a fairly complex taxonomic history. Synonyms include:

- *Eucalyptus tereticornis* var. *pruiniflora* (Blakely) Cameron
- *Eucalyptus insignis* Naudin
- *Eucalyptus populifolia* Desf.
- *Eucalyptus subulata* Schauer
- *Eucalyptus umbellata* (Gaertn.) Domin nom. illeg.
- *Eucalyptus umbellata var. pruiniflora* Blakely

There have also been numerous subspecies and varieties published, but the only ones that remain current are *E. tereticornis* subsp. *mediana* and the autonym *E. tereticornis* subsp. *tereticornis* . Together with the landrace variously known as 'Mysore gum', 'Mysore hybrid' or 'Eucalyptus hybrid', E. tereticornis accounted for 415 000 ha out of the total area of Eucalyptus trees reported as planted in India by 1974. It grows to a height of from 20 to 50 metres, and a girth of up to 2 metres dbh. The trunk is straight, and is usually unbranched for more than half of the total height of the tree. Thereafter, limbs are unusually steeply inclined for a *Eucalyptus* species. The bark is shed in irregular sheets, resulting in a smooth trunk surface coloured in patches of white, grey and blue, corresponding to areas that shed their bark at different times. *E. tereticornis* is a major source of pollen and nectar, producing a caramel-flavoured honey. E. tereticornis is popular and widely used for firewood and charcoal. In India , the most important use of *E. tereticornis* is for its good quality pulp and paper. The strength properties of the paper improve after the tree reaches 9 years of age, but the dark colour of the heartwood, in comparison with some other Eucalyptus species, is a disadvantage. It is also

Fig. 8: Eucalyptus: A general introduction of tree species

Published Eucalyptus Biomass Equations in India at a Glance

S.No	1
Title	Growth and above ground biomass in short rotation *Eucalyptus tereticornis* Sm. provenances.
Reference	Thakur,K. and Singh, I. (2005).Growth and above ground biomass in short rotation *Eucalyptus tereticornis* Sm. provenances.*Plant Archives.* 5(2): 441-445
Abstract	Field experiment was conducted during 2001-02 at Raipur, Chhattisgarh, India to determine the growth (diameter, height and survival percentage) and biomass estimates of *Eucalyptus tereticornis* plantations of different provenances. Seven provenances of *E. tereticornis* were from Australia, Bastar (Kondagaon), Bhubaneswar, Dhmatari (Sitanadi), Kolkata, Hisar (Haryana), and Raipur (Chhattisgarh). Increase in diameter was recorded at 6-month and 12-month intervals. Overall diameter increments for trees in all the Eucalyptus provenances ranged from 0.6-1.8 cm and 0.8-3.0 cm, respectively, after 6 and 12 months. The highest mean diameter increment in Raipur provenance after 6 and 12 months was 1.7 and 2.4 cm, respectively that occurred in 9-10 cm and 10-11 cm diameter classes and lowest was 0.73 and 0.80 cm which occurred in 2-3 diameter class. The aboveground biomass ranged from 9.99-21.69 t/ha in seven short rotations E. tereticornis provenances. The highest aboveground biomass was recorded in Raipur provenance (21.69 t/ha), while the lowest in Australian provenance (9.99 t/ha). The higher proportion of aboveground biomass was allocated to bole (60.4-63.3%) followed by branch (12.01-14.46%) and foliage (4.14-4.81%). On short-term basis it can be concluded that the provenance from Raipur, Kondagaon and Kolkata origin are superior over others and they should be planted in Chhattisgarh.
S.No.	2
Title	Biomass and productivity in short rotation Eucalyptus tereticornis Sm. seed sources grown in sub-humid dry tropical environment of India.
	Singh, I., Thakur,T. and Puri, S.(2005).Biomass and productivity in short rotation *Eucalyptus tereticornis* Sm.

Fig. 9: Bibliographic details of published Eucalyptus biomass equations in India

Published Volume Equations in India at a Glance

S.No	1
Title	Stand density and basal area prediction of unthinned irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India.
Reference	Tewari,V.P.(2007).Stand density and basal area prediction of unthinned irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. *Bioresource Technology*. 98(5): 1106-1114.
Abstract	Growth modelling is an essential prerequisite for evaluating the consequences of a particular management action on the future development of a forest ecosystem. Mathematical growth models are not available for many tree species in India. The objectives of this study were to estimate potential stand density and model the actual tree density and basal area development in pure even-aged stands of Eucalyptus camaldulensis. Relationships between quadratic mean diameter and stems ha-1 were developed, and parameter values of this relationship were used to establish the limiting density line. Two different models were compared to describe the natural decrease of stem number. The model including site index as one of the variables performed slightly better than the model without site index. Seven different stand level models also were compared for predicting basal area in the stands. The models tested in this paper belong to the path invariant algebraic difference form of a nonlinear model. They can be used to predict future basal area as a function of stand variables like initial basal area, age or dominant height, and stems ha-1 and are crucial for evaluating different silvicultural treatment options. The performance of the models for basal area was evaluated using different quantitative criteria. Among the seven models tested, the two models proposed by Pienaar and Shiver and Forss et al. had the best performance. The equations proposed to predict future basal area and stem number are related and, therefore, simultaneous regression technique has also been used to investigate the differences between parameter coefficients obtained by fitting the equations separately and jointly.
Model	Not Mentioned
S.No	2
Title	Total and merchantable wood volume equations for Eucalyptus hybrid trees in Gujarat State, India.
Reference	Tewari,V.P. and Singh,B.(2006). Total and merchantable wood volume equations for Eucalyptus hybrid trees in

Fig. 10: Bibliographic details of published eucalyptus volume equations in India

Fig. 11: Glimpses of Eucalyptus based experiments at NRCAF Research Farm

Bibliography

7. Ajit, Rai, P., Handa, A. K., Choudhari, S., Krishna Prasad, Y. V. and Pilli, A. B. (2005). Web enabled computerized databases on multipurpose trees in Indian Agroforestry: A holistic approach for information dissemination. In the proceedings - *Multipurpose Trees in the Tropics: Management & Improvement Strategies* (Eds. VP Tewari and RL Srivastava). Arid Forest Research Institute, Jodhpur, India. 462-269pp.

8. Ajit, Srivastava, P. N., Gupta, V. K. and Solanki, K. R. (2000)(b). Linear tree growth models: A limitation of negative estimation of size. *Indian Forester*. 126 (12): 1336-1341.

9. Amatayakul, W. and Azar, C. (2003). Eucalyptus plantations for electricity generation: The cost of carbon dioxide abatement in Thailand. *International Journal of Sustainable Development.* 6 (3): 359-377.

10. Anderson, J., Martin, M. E., Smith, M. L., Dubayah, R.O., Hofton, M. A, Hyde, P., Peterson, B. E., Blair, J. B. and Knox, R. G. (2006). The use of waveform lidar to measure northern temperate mixed conifer and deciduous forest structure in New Hampshire. *Remote Sensing of Environment*. 105: 248-261.

11. Andre, L. S., M'Bou, A. T., Maibala, A, Mouvondy, W., Jourdan, C., Roupsard, O., Deleporte, P., Hamel, O. and Nouvellon, Y. (2005). Age related equations for above and below ground biomass of a *Eucalyptus hybrid* in Congo. *Forest Ecology and Management*. 205: 199-214.

12. Annandale, M. (2002). Assessing the performance of 18 hardwood species / provenances on a black soil type in this region. *Hardwoods Queensland*

Research Update series: Species 586/2. Queensland Forestry Research Institute, Agency for Food and Fibre Sciences, DPI, Brisbane. http://www.pfnq.com.au/crrp%20growth%20rates.htm

13. Antonio, N., Margarida, T., Jose, T., Paula, S. and Luís, F. (2007). Effect of tree, stand, and site variables on the allometry of *Eucalyptus globulus* tree biomass . *Canadian Journal of Forest Research*. 37 (5): 895-906.

14. Aulokh, K. S. and Sandhu, S. S. (1990). Growth studies of some species and provenances of Eucalyptus in Punjab. *Indian Forester*. 116 (6): 442-445.

15. Bachpai, V. K. W., Pattanaik, S., Pathak, K. C., Bhuyan, T. C., Hazarika, K., Bhattacharyya, R. and Kharshi, I. A. (2005). Studies on growth behavior of some *Bambusa tulda* Roxb. plus clumps. *Indian Forester*. 131 (5): 711-718.

16. Bartelink, H. H. (1996). Allometric relationships on biomass and needle area of Douglas-fir. *Forest Ecology and Management*. 86: 193-203.

17. Berndes, G., Azar, C., Kaberger, T. and Abrahamson, D. (2001). The feasibility of large-scale lignocellulose-based Bioenergy production. *Biomass and Bioenergy*. 20: 371-83.

18. Bi, H. (1999). Predicting stem volume to any limit for native tree species in southern New South Wales and Victoria. *New Zealand Journal of Forestry Science*. 20: 318-331.

19. Bi, H. (2000). Trigonometric variable-form taper equations for Australian eucalyptus. *Forest Science*. 46: 397-409.

20. Bi, H. and Hamilton, F. (1998). Stem volume equations for native tree species in southern New South Wales and Victoria. *Australian Forestry*. 61: 275-286.

21. Bi, H. Q., Jurskis, V. and Gara, O. J. (2000). Improving height prediction of regrowth Eucalypts by incorporating the mean size of site trees in a modified Chapman-Richards equation. *Australian Forestry*. 63: 257-266.

22. Brown, A. G. (1989). Database applications in forestry research - an Australian experience. *Technical Paper*-143: 69-78. CATIE, Costa Rica.

23. Brown, S. (2002). Measuring carbon in forests: current status and future challenges. *Environmental Pollution*. 116: 363-372.

24. Bruce, D. and Schumacher, F. X. (1950). *Forest Mensuration*. McGraw-Hill Book company, Inc. New York. 483 pp.

25. Buford, M. A. (1986). Height-diameter relationship at age 15 in lobolly pine seed sources. *Forest Science*. 32: 812-818.

26. Cady, F. B., Pak, J. C. and Tabora, R. G. (1989). A user-friendly decision support system for multi-purpose tree research information - the F/FRED experience. *Technical Paper* -143: 62-68. CATIE, Costa Rica.

27. Cairns, M. A., Brown, S., Helmer, E. H., Baumgardner, G. A. (1997). Root biomass allocation in the world's upland forests. *Oecologia* .1 11:1-11.

28. Carlowitz, P. G. (1989). Establishing a multipurpose tree and shrub database-opportunities, limitations and problems. *Technical Paper*-143: 54-61. CATIE, Costa Rica.

29. Carmela, B. M., Arevalo., Volk, T. A., Bevilacqua, E. and Abrahamson, L. (2007). Development and validation of aboveground biomass estimation for four Salix clones in central New York. *Biomass and Bioenergy*. 31: 1-12.

30. Castedo, D. F., Diéguez-Aranda, U. and Álvarez-González, J. G. (2006). A growth model for *Pinus radiata* on stands in north-western Spain. *Annals of Forest Science.* 64 (4): 453-465.

31. Causton, D. (1985). Biometrical, structural and physiological relationships among tree parts. In: *Attributes of trees as crop plants*. (Eds: MGR Cannell and JE Jackson). Institute of Terrestrial Ecology, Huntingdon, UK. 137-159pp.

32. Causton, D. R. and Venus, J. C. (1981). The biometry of plant growth. *Edward Arnold.* London.

33. Cermelli, C., Fabio, A., Fabio, G. and Quaglio, P. (2008). Effect of eucalyptus essential oil on respiratory bacteria and viruses. *Current Microbiology*. 56 (1): 89-92.

34. Chandra, J. P., Yadav, M. P. S. and Gandhi, I. N. (1998). Performance of Eucalyptus species in Nainital Tarai of Uttar Pradesh. *Indian Forester*. 124 (3): 232-236.

35. Chaturvedi, A. N. (1973). Rotation in *Eucalyptus hybrid* plantations. *Indian Forester*. 99: 205-214.

36. Chaturvedi, A. N. and Khanna, L. S. (1982). *Forest Mensuration*. International Book Distribution, Dehradun.

37. Chaturvedi, A. N. and Sood, R. (1995). Variation in growth form and volume of clonal and seedling raised plants of *Eucalyptus hybrid*. *Journal of Tropical Forestry*. 11: 23-29.

38. Chauhan, H. S., Singh, K. and Patra, D. D. (1997). Performance of aromatic crops in Eucalyptus based agroforestry system. *Journal of Medicinal and Aromatic plant Sciences*. 19 (3): 724-728.

39. Chauhan, S. K., Chauhan, R. and Sharma, S. C. (2008). Economic and environmental viability of short rotation forestry. In Proceedings of National Symposium on '*Intensive forest farming: The State of the Art*' held during Feb 12-14, 2008 at PAU, Ludhiana.16-19 pp.

40. Choubey, A. K., Mahagani, P. H., Bhartari, B. K. and Kukreti, K. M. (1990). Determination of sample size for estimating the volume of Eucalyptus in an agro-forestry situation. *Indian Forester*. 116: 37-41.

41. Crow, T. R. and Schlaegel, B. E. (1988). A guide to using regression equations for estimating tree biomass. *Northern Journal of Applied Forestry*. 5: 15-22.

42. Curtis, R. O. (1967). Height-diameter and height-diameter-age equations for second growth Douglas-fir. *Forest Science*. 13: 365-375.

43. Datta, M. and Singh, N. P. (2007). Growth Characteristics of Multipurpose Tree Species, Crop Productivity and Soil Properties in Agroforestry Systems under Subtropical Humid Climate in India. *Journal of Forestry Research*. 18 (4): 261-270.

44. Delphis, F. and Levia, J. R. (2008). A generalized allometric equation to predict foliar dry weight on the basis of trunk diameter for eastern white pine (*Pinus strobus* L.). *Forest Ecology and Management*. 255 (5-6): 1789-1792.

45. Dhawan, M. (1990). A rapid method for leaf area estimation in *Eucalyptus hybrid* seedlings. *Indian Journal of Forestry*. 13: 167-168.

46. Dhyani, S. K. and Tripathi, R. S. (1998). Tree growth and crop yield under agrisilvicultural practices in north east India. *Agroforestry Systems*. 44 (1): 1-12.

47. Dogra, A. S. and Sharma, S. C. (2003). Volume prediction equations for *Eucalyptus hybrid* in Punjab. *Indian Forester*. 129: 1451-1460.

48. Dogra, A. S. and Upadhyay, A. (2005). Site index equations for *Eucalyptus hybrid* in Punjab. *Indian Forester*. 131: 487-498.

49. Drapper, N. and Smith, H. (1982). *Applied regression Analysis*. 2nd Edition. John Wiley and Sons. New York. USA.

50. Dutt, D., Tyagi, C. H., Upadhyaya, J. S. and Singh, S. (2007). Development of specialty papers is an art: Playing cards base paper from *Eucalyptus tereticornis*, *Leucaena Leucocephala* and *Bambusa Aurandacea* -Part XV. IPPTA: *Quarterly Journal of Indian Pulp and Paper Technical Association*. 19 (3): 153-155.

51. Eamus, D., McGuinness, K. and Burrows, W. (2000). Review of allometric relationship for estimating woody biomass for Queensland, the Northern Territory and Western Australia. Aust Greenhouse Office, Canberra. In: *National Carbon Accounting System Technical Report*. 5A: 1–56.

52. Ellis, E. A., Nair, P. K. R. and Jeswani, S. D. (2005). Development of a web-based application for agroforestry planning and tree selection. *Computers and Electronics in Agriculture*. 49 (1): 129-141.

53. Ellis, E. A. and Schoeneberger, M. M. (2004). Computer-based tools for decision support in agroforestry: Current state and future needs. *Agroforestry Systems*. 61-62 (1-3): 401-421.

54. Faiz, M., Singh, R. P. and Rajput, D. K. (2003). Biomass of *Eucalyptus hybrid* plantations under agroforestry system. *Indian Forester*. 129 (8): 1037-1040.

55. FAO. (2007). http://www.fao.org/ag/AGP/AGPC/doc/GBASE/latinsearch.htm

56. Feng, F. L. (1997). Modeling stand growth varies in response to different spacing. *Quarterly Journal of the Experimental Forest of National Taiwan University*. 11: 111-123.

57. Ferreira, C. A. and Trevisan, R. (2001). Projection of the volumetric growth of *Eucalyptus species* in the *Brazilian southern region. Boletim de Pesquisa Florestal.* 42: 71-82.

58. Garcia, O. and Ruiz, F. (2003). A growth model for eucalypt in Galicia, Spain. *Forest Ecology and Management*. 173: 49-62.

59. Geisser, S. (1975). The predictive sample reuse method with application. *Journal of American Statistics Association*. 70: 320-328.

60. Gill, A. S. and Ajit. (2004). Classification of multipurpose tree species on the basis of their growth attributes under tree crop interface in semi arid conditions: A clustering approach. *Indian Forester*. 130 (2): 173-180.

61. Gill, A. S. and Ajit. (2005). Growth performance of trees under varying spacing with and without crops in their inter spaces in semi arid conditions. *International Journal of Forest Usufructs Management*. 6 (1): 19-27.

62. Gill, A. S., Roy, R. D., Chaudhary, B. L. and Handa, A. K. (2001). Performance of agroforestry tree species for their biomass production under semiarid condition. *Flora and Fauna*. 7 (1): 3-4.

63. Gompertz, B. (1825). On the nature of the function expressive of the law of human mortality and on the new mode of determining the value of life contingencies. *Philosophical Transactions of the Royal Society of London*. 115: 513-585.

64. Goulding, C. J. (1979). Validation of growth models used in forest management. *New Zealand Journal of Forestry*. 24:108-124.

65. Grundy, L. M. (1995). Woody biomass estimation in dry *miombo* woodland in Zimbabwe. *Forest Ecology and Management*. 72: 109-117.

66. Guo, L. B., Sims, R. E. H. and Horne, D. J. (2006). Biomass production and nutrient cycling in Eucalyptus short rotation energy forests in New Zealand: II. Litter fall and nutrient return. *Biomass and Bioenergy*. 30 (5): 393-404.

67. Gupta, R. K., Agarwal, M. C. and Kumar, N. (1996). Growth and phytomass production in *Leucaena leucocephala* under high density plantations on degraded lands of Doon Valley. *Indian Forester*. 122: 241-246.

68. Hall, G. G. (1963). The application of mathematical thinking. University of Nottingham Press.

69. Hann, D. W. (2004). http://www.cof.orst.edu/cof/fr/research/organon/orginf.htm

70. Harmand, J. M., Njiti, C. F., Reversat, F. B. and Puig, H. (2004). Aboveground and belowground biomass, productivity and nutrient accumulation in tree improved fallows in the dry tropics of Cameroon. *Forest Ecology and Management*. 188 (1-3): 249-265.

71. Hart, P. B. S., Clinton, P. W., Allen, R. B., Nordmeyer, A. H. and Evans, G. (2003). Biomass and macro-nutrients (above-and below ground) in a New

Zealand beech forest ecosystem: implications for carbon storage and sustainable forest management. *Forest Ecology and Management*. 174: 281-294.

72. Hellden, U. (1987). An assessment of woody biomass, community forests, land use and soil erosion in Ethiopia. A Feasibility Study on the Use of Remote Sensing and GIS-analysis for Planning Purposes in Developing Countries. *Land Studies in Geography, Ser. C. General, Mathematical and Regional Geography*, No. 14, Lund. Sweden.

73. Henson, M., Smith, H. and Boyton, S. (2007). *Eucalyptus longirostrata*: a potential species for Australia's tougher sites? Australasian Forest Genetics Conference: Breeding for Wood Quality Incorporating meetings of the Australasian Forestry Research Working Group 1 (Genetics) and the IUFRO Southern pine working group (2.02.20), 11 - 14 April, The Old Woolstore, Hobart, Tasmania, Australia.

74. Huang, S. and Titus, S. J. (1992). Comparison of nonlinear height-diameter functions for major Alberta tree species. *Canadian Journal of Forest Research*. 22: 1297-1304.

75. Hunter, I. (2001). Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulensis, Eucalyptus grandis* and *Dalbergia sissoo*) as affected by irrigation and fertilizers, at 3 years of age, in Southern India. *Forest Ecology and Management.* 144: 189-199.

76. Husch, B., Miller, C. I. and Beers, T. W. (1982). *Forest Mensuration*. 3rd edition. The Roland Press Co., New York. 402 pp.

77. Hutchinson, G. E. (1978). *An introduction to population ecology*. Yates University Press, New Haven, CT.

78. Inoue, A. and Yoshida, S. (2004). Allometric model of the height-diameter curve for even-aged pure stands of Japanese cedar (*Cryptomeria japonica*). *Journal of Forest Research*. 9 (4): 325-331.

79. Jain, R. C., Rai, M. P. and Rawat, J. K. (1991). Application of 'piecewise fitting of a model' technique in construction of volume tables. *Indian Forester*. 117: 1036-1040.

80. Jain, R. C., Singh, J., Gurdev. and Rawat, J. K. (1993)(a). Volume tables for *Eucalyptus globulus* plantations in Nilgiri Hills. *Indian Forester*. 119 (12): 994-998.

81. Jain, R. C., Singh, J., Gurdev. and Rawat, J. K. (1993)(b). Volume tables for *Eucalyptus camaldulensis* plantations. *Indian Forester*. 119 (6): 460-465.

82. Jain, R. C., Tripathi, S. P., Kishan, V. S. and Kumar, S. (1996). Volume tables for *Acacia tortilis* plantations based on data collected from kjd abadi plantations of khajuwala range Chattergarh Division, IGNP area, Rajasthan. *Indian Forester*. 122: 316-322.

83. Jain, R. C., Tripathi, S. P., Singh, M. and Kumar, V. K. S. (1998). Volume tables for *Azadirachta indica* for Gujrat region. *Indian Forester*. 124: 123-133.

84. Janssen, P. H. M. and Titus, S. J. (1995). Calibration of process oriented models. *Ecological Modelling.* 83: 55-66.

85. Jara, N. L. F. (1991). Provenance trials of *Eucalyptus saligna* in the province of Antioquia, Colombia In: *Forest Genetic Resources Information (FAO).* 19: 20-24.

86. Jenkins, J. C., Chojnacky, D. C., Heath, L. S. and Birdsey, R. (2004). Comprehensive database of diameter-based biomass regressions for North American tree species. United States Department of Agriculture, Forest Service, *General Technical Report.* NE-319: 1–45.

87. Jenkins, J. C., Chojnacky, D. C., Heath, L. S. and Birdsey, R. A. (2003). National-scale biomass estimators for United States tree species. *Forest Science.* 49: 12–35.

88. Kajimoto, T., Matsuura, y., Osawa, A., Abaimov, A. P., Zyryanova, O. A., Isaev, A. P., Yefremov, D. P., Mori, S. and Kioke, T. (2006). Size-mass Allometry and biomass allocation of two larch species growing on the continuous perma-frost region in Siberia. *Forest Ecology and Management.* 222: 314-325.

89. Kallarackal, J. and Somen, C. K. (2008). Water loss from tree plantations in the tropics. *Current Science.* 94 (2): 201-210.

90. Keith, H., Barrett, D. and Keenan, R. (2000). Review of allometric relationship for estimating woody biomass for New South Wales, the Australian Capital Territory, Victoria, Tasmania and South Australia. In: The Australian Greenhouse

Office, Canberra, *National Carbon Accounting System Technical Report*. 5B: 1–113.

91. Khan, G. S. and Chaudhry, A. K. (2007). Effect of spacing and plant density on the growth of poplar (*Populus deltoides*) trees under agro-forestry system. *Pakistan Journal of Agricultural Sciences*. 44 (2): 321-327.

92. Kitchen, N. R. (2008). Emerging technologies for real-time and integrated agriculture decisions. *Computers and Electronics in Agriculture*. 61 (1): 1-3.

93. Kostler, J. N., Bruckner, E. and Biblriether, H. (1986). Die Wurzeln der Waldbaume, Unteruchungen zur Morphologie der Waldbaume in Mitteleuropa. *Verlag Paul Parey*. Hamburg and Berlin. 282 pp.

94. Kulkarni, M. B. and Gore, A. P. (1988). Improvement in volume estimation by adding one more girth observation. *Van Vigyan*. 26: 1-4.

95. Kumar, R. and Bangarwa, K. S. (2006). Clonal evaluation in *Eucalyptus tereticornis* Sm. *Environment and Ecology*. 24: 1188-1191.

96. Kumar, V., Nagawani, H. C., Kumar, D. and Singh, V. P. (1996). Propagation and growth studies of *Calligonum polygonoides* (Phog). *Indian Forester*. 122: 377-382.

97. Kunisaki, T. and Imada, M. (1996). Tree diameter distribution of stands and each species in large scale cool temperate forest of Kyushu, southern Japan. *Journal of the faculty of Agriculture Kyushu University*. 41: 45-46.

98. Kurlz, W. A., Beukema S. J. and Apps, M. J. (1996). Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector. *Canadian Journal of Forest Research*. 26: 1973-1979.

99. Kushalappa, K. A. (1984). Biomass of Mysore gum trees in Jedigenahally, Karnataka. *Indian Forester*. 110: 854-860.

100. Laclau, J. P., Bouillet, J. P., Gonçalves, J. L. M., Silva, E. V., Jourdan, C., Cunha, M. C. S., Moreira, M. R., Saint-André L., Maquère, V., Nouvellon, Y. and Ranger, J. (2008). Mixed-species plantations of *Acacia mangium* and *Eucalyptus grandis* in Brazil: 1. Growth dynamics and aboveground net primary production. *Forest Ecology and Management*. 255 (12): 3905-3917.

101. Laird, A. K., Tyler, S. A. and Barton, A. D. (1965). Dynamics of normal growth. *Growth*. 29: 233-248.

102. Lal, P. (2003). Clonal Eucalyptus Plantations in India. *Eucalyptus in Asia* (Ed: JW Turnbull). Proceedings of International Conference, Zhanjiag, China, April 7-11, ACIAR Proceeding No. 111, Canberra, Australia.

103. Lal, P. (2007). R & D priorities for Clonal plantations. *Indian Forester*. 133 (12): 1581-1589.

104. Lal, P. (2008). Clonal eucalyptus plantation in India. In Proceedings of National Symposium on '*Intensive forest farming: The State of the Art*' held during Feb 12-14, 2008 at PAU, Ludhiana. 3-6 pp.

105. Lal, P., Dogra, A. S., Sharma, S. C. and Chahal, G. B. S. (2006). Evaluation of different clones of Eucalyptus in Punjab. *Indian Forester*. 132 (11): 1383-1390.

106. Landis, E., Palmer, C., Aguirre Bravo, C. and Franco, C. R. (1999). Global strategy for forest information exchange. Paper-12: 425-429. Rocky Mountain Research Station, USDA Forest Service, U.S.A.

107. Landsberg, J. J. and Waring, R. H. (1997). A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management.* 95: 209-228.

108. Law, B. E., Van Tuyl, S., Cescatti, A. and Baldocchi, D. D. (2001). Estimation of leaf area index in open-canopy ponderosa pine forests at different successional stages and management regimes in Oregon. *Agricultural and Forest. Meteorology*. 108: 1-14.

109. Leakey, R. R. B. and Sanchez, P. A. (1997). How many people use agroforestry products?. *Agroforestry Today*. 9 (3): 4-5.

110. Loomis, R. M., Phares, R. E. and Crosby, J. S. (1966). Estimating foliage and branch wood quantities on shortleaf pine. *Forest Science*. 12: 30-39.

111. Lootens, J. R., Larsen, D. R. and Shifley, S. R. (2007). Height-diameter equations for 12 upland species in the Missouri Ozark highlands. *Northern Journal of Applied Forestry*. 24 (2): 149-152.

112. Luna, R. K. and Chamoli, N. (2008). Evaluation of quality of seedlings raised under agro-net shade and direct sunlight. *Indian Forester*. 134 (1): 17-25.

113. Maiti, S. K. (2007). Bioreclamation of Coalmine Overburden dumps-with Special Empasis on Micronutrients and Heavy Metals Accumulation in Tree Species. *Environmental Monitoring and Assessment.* 125 (1-3): 111-122.

114. Malimbwi, R. E., Solberg, B. and Luoga, E. (1994). Estimation of biomass and volume in miombo woodland at Kitungalo Forest Reserve, Tanzania. *Journal of Tropical Forest Science.* 7: 230-242.

115. Mani, S. and Parthasarathy, N. (2007). Above-ground biomass estimation in ten tropical dry evergreen forest sites of peninsular India. *Biomass and Bioenergy*. 31 (5): 284-290.

116. Marklund, L. G. (1987). Biomass functions for Norway spruce (*Picea abies* (L.) Karst.) in Sweden. Sveriges lantbruksuniversitet, Rapporter–Skog. 43: 1–127.

117. Mason, E. G. and Whyte, A. G. D. (1997). Modeling initial survival and growth of radiata pine in New Zealand. *Acta Forestalia Fennica*. 255:38 pp.

118. Mayer, D. G. and Butler, D. G. (1993). Statistical validation. *Ecological Modelling*. 68: 21-32.

119. Mayer, W. J. (1985). *Concepts of mathematical modeling*. McGraw-Hill Book Company, New York.

120. Mclone, R. R and Andersons, J. G. (1976). *Mathematical modeling*. Butter worth group, London (UK).

121. Mehtatalo, L. (2005). Height-Diameter models for scots pine and birch in Finland. *Silva Fennica*. 39 (1): 55-66.

122. Mishra, V. K. and Nayak, B. K. (2000). Biomass productivity of energy plantations on Himalayan foothill. *Environment and Ecology*. 18 (1): 13-16.

123. Moffat, A. J., Matthews, R. W. and Hall, J. E. (1991). The effect of sewage sludge on growth and soil chemistry in pole stage corsican pine at Ringwood Forest, Dorset, UK. *Canadian Journal of Forest Research*. 21: 902-909.

124. Monserud, R. A. and Marshall, J. D. (1999). Allometric crown relations three northern Idaho conifer species. *Canadian Journal of Forest Research*. 29: 521-535.

125. Montagu, K. D., Duttmer, K., Barton, C. V. M., and Cowil, A. L. (2005). Developing general allometric relationships for regional estimates of carbon sequestration-an example using *Eucalyptus pilularis* from seven contrasting sites. *Forest Ecology and Management*. 204: 113-127.

126. Munoz, F., Rubilar, R., Espinosa, M., Cancino, J., Toro, J. and Herrera, M. (2008). The effect of pruning and thinning on above ground aerial biomass of *Eucalyptus nitens* (Deane & Maiden) Maiden. *Forest Ecology and Management*. 255 (3-4): 365-373.

127. N. R. C (National Research Council). (2000). Biobased industrial products: priorities for research and commercialization. Washington, DC: National Academy Press.

128. Nagaveni, H. C. and Vijayalakshmi, G. (2002). Effect of VAM and Azotobacter inoculation on growth and biomass production in forestry species. *Indian Journal of Forestry*. 25 (3/4): 286-290.

129. Nair, R., Vaghasiya, Y. and Chanda, S. (2008). Antibacterial activity of *Eucalpytus citriodora* Hk. oil on few clinically important bacteria. *African Journal of Biotechnology*. 7 (1): 25-26.

130. Nasir, M. A., Aziz. A., Mohar, T. A., Rehman, M. A. and Saeed, A. (2006). Effect of planting distance on tree growth and fruit quality of shamber grape fruit under agro climatic conditions of Sargodha. *Journal of Agricultural Research Lahore*. 44 (4): 353-358.

131. Naugraiya, M. N. and Puri, S. (2001). Performance of multipurpose tree species under agroforestry systems on entisols of Chhattisgarh plains. *Range Management and Agroforestry*. 22: 164-172.

132. Negi, J. D. S. and Sharma, D. C. (1987). Biomass estimation of two Eucalyptus species by regression method. *Indian Forester*. 113: 180-184.

133. Nerd, A. Irijimovich, V. and Mizrahi, Y. (1998). Phenology, breeding system and fruit development of argan (*Aragania spinosa*, Sapotaceae) cultivated in Israel. *Economic Botany*. 52: 161-167.

134. Nokea, S. (1978). Demonstrating the flexibility of the Gompertz function as a yield model using mature tree species data. *Commonwealth Forest Review*. 57: 35-42.

135. Olsson, K. (1985). Remote sensing for fuelwood resources and land degradation studies in Kordofan, the Sudan, *Ph.D. Thesis*. Meddelanden fran lunds Universities Geografiska Institution, Avhandlingar. 182pp.

136. Pal, M. and Raturi, D. P. (1991). Growth, biomass production and dry matter distribution pattern of *Eucalyptus hybrid* grown in an energy plantation. *Indian Forester*. 117: 187-192.

137. Pande, G. C. (1974). Volume prediction in *Eucalyptus grandis* crops. *Indian Forester*. 100 (9): 533-543.

138. Pande, G. C. and Chaturvedi, A. N. (1972). Stand volume, weight tables and other crop studies in Mysore Gum (*Eucalyptus hybrid*). *Indian Forester*. 98: 286-297.

139. Pande, G. C. and Jain, R. C. (1976). Tree volume tables for *Eucalyptus grandis*. *Indian Forester*. 102: 362-387.

140. Pastor, J., Aber, J. D. and Melillo, J. M. (1983/1984). Biomass prediction using generalized allometric regressions for some northeast tree species. *Forest Ecology and Management*. 7: 265–274.

141. Patil, S. J., Nadagoudar, B. S., Mutanal, S. L., Madiwalar, S. L. and Devaranavadgi, S. B. (2000). Suitability of tree species in an agroforestry system in hill zone of Karnataka. *Indian Forester*. 126 (11): 1187-1190.

142. Pearson, J. A., Fathey, T. J. and Knight, D. H. (1984). Biomass and leaf area in contrasting lodgepole pine forests. *Canadian Journal of Forest Research*. 14: 259-265.

143. Planning Commission. (2001). *Report of the Task Force on Greening India for livelihood security and sustainable development*. Government of India.

144. Prajapati, R. C. (1993). Local volume equation for eucalyptus pole crop. *Myforest*. 29: 256-257.

145. Prajapati, R. K., Singh, R. S. and Singh, L. (2006). Growth and biomass production of multipurpose trees planted in chronosequence pure and mixed stands on limestone mine overburden in Chattishgarh. *Indian Journal of Tropical Biodiversity*. 14 (2): 190-194.

146. Prajneshu. and Chandran, K. P. (2005). Competition of compound growth rates in agriculture: Revisited. *Agricultural Economics Research Review*. 18: 317-324.

147. Prasad, U. (1984). Trial of Eucalyptus F.R.I.-4 and F.R.I.-5 on different doses of manure. *Indian Forester*. 110 (2): 129-131.

148. Putter, A. (1920). Investigation of physiological similarities of growth processes. . *Gastric Physiology*. 180: 298-340.

149. Rai, S. N. (1984)(a). Above ground biomass in tropical rain forests of Western Ghats in India. *Indian Forester*. 110: 754-764.

150. Rai, S. N. (1984)(b). Bole, branch, current year twig, leaf and root biomass production in tropical rain (wet evergreen) forests of Western Ghats of Karnataka. *Indian Forester*. 110: 901-914.

151. Raj, D. and G. S. Cheema. (1990). Nursery trial of *Poplar* clones. *Journal of Tropical Forestry*. 6: 201-207.

152. Rana, B. S., Parihar, A. K. S. and Singh, B. P. (2002). Growth pattern of certain MPTS raised on sodic land. *Indian Forester*. 128 (6): 674-680.

153. Rana, B. S., Saxena, A. K., Rao, O. P. and Singh, B. P. (2007). Nutrient return to the soil through litterfall under certain tree plantations on sodic wastelands in northern India. *Journal of Tropical Forest Science*. 19 (3): 141-149.

154. Rao, C. R., Mitra, S. K., Maithai, A. and Ramamurthy, K. G. (1985). *Formula and tables for statisticallVorks*. Statistical Publishing Society, Calcutta, India.

155. Rao, R.V., Shashikala, S., Sreevani, P. and Kothiyal, V. (2005). Clonal variation in basic density and anatomical properties of *Eucalyptus tereticornis* - four to five years. *Indian Forester*. 131 (9): 1187-1200.

156. Ratkowsky, D. A. (1990). *Handbook of Nonlinear Regression Models*. Marcel Dekker, New York, 241pp.

157. Rawat, J. K. (1990). Economic spacing and rotation decisions in farm forestry. *Indian Forester*. 116 (5): 341-347.

158. Rayner, M. E. (1992). Evaluation of six site classifications for modelling timber yield of regrowth karri (*Eucalyptus diversicolor F. Muell.*). *Forest Ecology and Management*. 54: 315-336.

159. Reed, D. D. and Green, E. J. (1985). A method of forcing additivity of biomass tables when using nonlinear models. *Canadian Journal of Forest Research*. 15: 1184-1187.

160. Reed, D. D. and Tome, M. (1998). Total aboveground biomass and net dry matter accumulation by plant component in young Eucalyptus globules in response to irrigation. *Forest Ecology and Management*. 103: 21-32.

161. Reed, D. D., Jones, E. A., Tome, M. and Araujo, M. C. (2003). Models of potential height and diameter for *Eucalyptus globulus* in Portugal. *Forest Ecology and Management*. 172: 191-198.

162. Reynolds, M. R. and Chung, J. (1986). Regression methodology for estimating model prediction error. *Canadian Journal of Forest Research*. 16: 931-938.

163. Reynolds, M. R., Burk, T. E. and Huang, W. (1988). Goodness of fit tests and model selection procedures for diameter distribution models. *Forest Science*. 34: 373-399.

164. Richard, J. B. (2006). Mosquito Repellent Effectiveness: A Placebo Controlled Trial Comparing 95% DEET, Avon Skin so Soft, and a "special Mixture" Containing Eucalyptus Oil. *British Colombia Medical Journal*. 48 (5): 226-231.

165. Richards, F. J. (1959). A flexible growth function for empirical use. *Journal of Experimental Botany*. 10: 290-300.

166. Richards, F. J. (1969). The quantitative analysis of growth. In *Plant Physiology VA* (Ed. FC.Steward). 3-76 pp.

167. Ritu. (2006). Analysis and Modeling of Eucalyptus based Systems in Bundelkhand Region. *Ph.D thesis*. Bundelkhand University, 206.

168. Rose, D. W. (1989). Database applications in tropical forestry. *Technical Paper* - 143: 1-6. CATIE, Costa Rica.

169. Salim, A. S., Simons, A. J., Waruhiu, A., Orwa, C. and Anyango, C. (1998). Agroforestree database – A tree species reference and selection guide ver 1.0 on CD-ROM. ICRAF, Kenya.

170. Sankaran, K. V., Mendham, D. S., Chacko, K. C., Pandalai, R. C., Grove, T. S. and O'Connell, A. M. (2007). Increasing and sustaining productivity of tropical eucalypt plantations over multiple rotations. *Journal of Sustainable Forestry*. 24 (2-3): 109-121.

171. Santantonio, D. (1990). Modelling growth and production of tree roots. In Process Modelling of Forest Growth Responses to Environment Stress. (Eds: RK. Dixon,

RS. Meldahl, GA. Ruark and WG. Warren). Timber Press, Portland, Oregon. 124-141 pp.

172. Saporito, L. (2003). An allometric function for eucalyptus in Central Sicily. *Sherwood Foreste-ed- Alberi Oggi*. 9: 29-33.

173. Schmitt, M. D. C. and Grigal, D. F. (1981). Generalized biomass estimation equation for *Betula papyrifera* Marsh. *Canadian Journal of Forest Research*. 11: 837–840.

174. Schroder, J. M. and Jaenicke, H. (1994). A computerised database as decision support tool for the selection of agroforestry tree species. *Agroforestry Systems*. 26 (1): 65-70.

175. Sharma, M. and Parton, J. (2007). Height–diameter equations for boreal tree species in Ontario using a mixed-effects modeling approach. *Forest Ecology and Management*. 249 (3): 187-198.

176. Sharma, R. P. (1978). Weight tables and volume-weight relation for *Eucalyptus hybrid* [based on data from Bijnor Plantation Division, Uttar Pradesh]. *Indian Forester*. 104: 554-557.

177. Shibuya, M., Yajima, T. and Matsuda, K. (1997). A modified stand density control diagram for Japanese white birch based on a trend of mean volume-density relationships with stand growth. *Research Bulletin of the Hokkaido University Forests*. 54: 202-211.

178. Singh, C., Vishwanatham, M. K., Kumar, N. and Agarwal, M. C. (1998). Growth, survival and MAI of Ban oak on degraded lands of Doon Valley. *Indian Forester*. 124: 732-738.

179. Singh, J., Singh, O., Negi, M. S. and Banwal, N. R. (1995). Regional volume tables for *Eucalyptus hybrid* (based on data from Muzaffarnagar). *Indian Forester*. 121: 365-370.

180. Singh, O., Sharma, D. C. and Rawat, J. K. (1992). Biomass and nutrient release in natural Sal, eucalyptus and poplar plantations of Uttar pradesh. *Van Vigyan*. 30 (3&4): 134-140.

181. Singh, S. and Sharma, S. K. (2005). Antibacterial activity of essential oil and root extract of *Eucalyptus tereticornis*. *Indian Journal of Natural Products*. 21 (1): 16-17.

182. Sladoba, B. (1971). Investigation of growth processes using first order differential equations. Mitteilunger der Baden Wurttembergischen Forstlichen Versuchs-und For schungsanstalt, Heft 32 [In German].

183. Snowdon, P., Eamus, D., Gibbons, P., Khanna, P., Keith, H., Raison, J. and Kirschbaum, M. (2000). Synthesis of allometrics, review of root biomass and design of future woody biomass sampling strategies. In: The Australian Greenhouse Office, Canberra, *National Carbon Accounting System Technical Report*. 17: 1–114.

184. Snowdon, P., Raison, J., Keith, H., Grierson, P., Adams, M.A., Montagu, K., Hui-Quan, B., Burrows, W. and Easmus, D. (2002). Protocol for sampling tree and stand biomass. *Technical Report, 31*. Australian Greenhouse Office, Canberra, Australia.

185. Soares, P. and Tome, M. (2002). Height-diameter equation for first rotation of Eucalyptus plantations in Portugal. *Forest Ecology and Management*. 166 (1-3): 99-109.

186. Soares, P. and Tome, M. (2003). GLOBTREE: an individual tree growth model for *Eucalyptus globulus* in Portugal. In Proceeding of *Modelling of forest systems. Workshop on the interface between reality, modeling and the parameter estimation processes, Sesimbra, Portugal.* 97-110 pp.

187. Soares, P., Tome, M., Skovsgaard. and Vanlacy. (1995). Evaluating a growth model for forest management using continuous forest inventory data. *Forest Ecology and Management*. 71: 251-265.

188. Sochacki, S. J., Harper, R. J. and Smettem, K. R. J. (2007). Estimation of woody biomass production from a short-rotation bio-energy system in semi-arid Australia. *Biomass and Bioenergy*. 31 (9): 608-616.

189. Specht, A. and West, P. W. (2003). Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia. *Biomass and Bioenergy*. 25: 363-379.

190. Stape, J. L., Binkley, D. and Ryan, M. G. (2008). Production and carbon allocation in a clonal Eucalyptus plantation with water and nutrient manipulations. *Forest Ecology and Management*. 255 (3-4): 920-930.

191. Stromgaard, P. (1985). Biomass estimation equations for miombo woodland, Zambia. *Agroforestry Systems*. 3: 3-13.

192. Stukely, M. J. C., Crane, C. E., McComb, J. A. and Bennett, I. J. (2007). Field survival and growth of clonal, micropropagated *Eucalyptus marginata* selected for resistance to *Phytophthora cinnamomi*. *Forest Ecology and Management*. 238 (1-3): 330-334.

193. Sudha, P., Ramprasad, V., Nagendra, M. D. V., Kulkarni, H. D. and Ravindranath, N. H. (2007). Development of an agroforestry carbon sequestration project in Khammam district, India. *Mitigation and Adaptation Strategies for Global Change*. 12 (6): 1131-1152.

194. Sundararaju, R., Bharathi, R. K. and Chinnathurai, A. K. (1995). Provenance trial of *Eucalyptus tereticornis*. *Indian Forester*. 121 (2): 96-102.

195. Surey, R., Sharma, M. C. and Tiwari, K. P. (1999). Volume tables of *Eucalyptus hybrid* (main crop) for Madhya Pradesh. *Journal of Tropical Forestry*. 15: 121-128.

196. Swamy, S. L., Mishra, A. and Bharitya, J. K. (2007). Growth, productivity and nutrient uptake in wheat under different spacings of Gmelina arborea in agri-silviculture system. *Journal of Soils and Crops*. 17 (2): 198-203.

197. Tandon, V. N., Pande, M. C. and Singh, R. (1988). Biomass estimation and distribution of nutrients in five different aged *Eucalyptus grandis* plantation ecosystems in Kerala state. *Indian Forester*. 114: 184-199.

198. Tandon, V. N., Rawat, J. K. and Singh, R. (1993). Biomass production and mineral cycling in plantation ecosystems of *Eucalyptus hybrid* in Haryana. 1. Biomass production and its distribution. *Indian Forester*. 119 (3): 232-237.

199. Tang, S. (1994). Self adjusted height-diameter curves and one entry volume model. *Forest Research*. 7 (5): 512-518.

200. Ter-Mikaelian, M. T. and Korzukhin, M. D. (1997). Biomass equations for sixty-five North American tree species. *Forest Ecology and Management*. 97: 1-24.

201. Tewari, V. P. and Kumar, V. S. K. (2003)(a). Volume equations and their validation for irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. *Journal of Tropical Forest Science*. 15 (1): 136-146.

202. Tewari, V. P. (1996). Developing equations for estimating growth parameters of *Acacia tortilis*. *Indian Forester*. 122: 1004-1009.

203. Tewari, V. P. and Gadow, K. V. (2003). Preliminary growth models for *Prosopis cineraria* (L.) Druce plantations in the hot arid region of India. *Forests Trees and Livelihoods*. 13 (4): 361-373.

204. Tewari, V. P. and Kumar, V. S. K. (2003)(b). Spacing effect on the height-diameter relationship of irrigated shelterbelt plantations in hot desert. *Indian Forester*. 129: 349-356.

205. Tewari, V. P., Kumar, V. S. K. and Singh, B. (2001). Volume equations for *Eucalyptus camaldulensis* in Indira Gandhi Nahar Pariyojana (IGNP) area. *Indian Forester*. 127: 1367-1370.

206. Tewari, V. P., Rivas, J. J. C., Vilcko, F. and Gadow, K. V. (2007). Height-growth and site index equations for social forestry plantations of *Acacia nilotica* and *Eucalyptus hybrid* in Gujarat State of India. *Forests Trees and Livelihoods*. 17 (2): 125-140.

207. Tewari, V. P., Verma, A. and Kumar V. S. K. (2002). Growth and yield functions for irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. *Bioresource Technology*. 85: 137-146.

208. Thaker, V. S. and Singh, Y. D. (2001). Selection of tree species for energy plantation in arid-semi arid area: Comparative growth studies. *Indian Forester*. 127: 678-684.

209. Thakur, T. and Singh, L. (2005). Growth and above ground biomass in short rotation *Eucalyptus tereticornis* Sm. provenances. *Plant Archives*. 5 (2): 441-445.

210. Thornley, J. H. M. and Johnson, I. R. (1990). *Plant and crop modeling*. Oxford University Press, Oxford, UK.

211. Tietema, T. (1993). Biomass determination of fuelwood trees and bushes of Botswana, southern Africa. *Forest Ecology and Management*. 60 (3-4): 257-269.

212. Tokyo, O. P., Bisht, R. P., Kumar, N. and Singh, R. R. (1994). Growth and biomass of *Populus deltoides* grown at three plant spacings in arid India. *Indian Journal of Forestry*. 17: 301-304.

213. Tripathi, P., Dubey, N. K. and Shukla, A. K. (2008). Use of some essential oils as post-harvest botanical fungicides in the management of grey mould of grapes caused by *Botrytis cinerea* . *World Journal of Microbiology and Biotechnology*. 24 (1): 39-46.

214. Turner, J. and Lambert, M. J. (2008). Nutrient cycling in age sequences of two Eucalyptus plantation species. *Forest Ecology and Management*. 255 (5-6): 1701-1712.

215. Varma, R. V. and Swaran, P. R. (2007). Diversity of termites in a young Eucalypt plantation in the tropical forests of Kerala, India. *International Journal of Tropical Insect Science*. 27 (2): 95-101.

216. Venkatesh, G. S. and Sharma. V. (1977). Rapid growth rate and higher yield potential of heterotic Eucalyptus species hybrids FRI-4 and FRI-5. *Indian Forester*. 103 (12): 795-802.

217. Venkateswarlu, P. (1994). Multipurpose software for multipurpose trees. *Agroforestry Today*. 6 (4): 16-17.

218. Verhulst, P. F. (1838). A note on population growth. *Correspondence Mathematiques et. Physiques*. 10: 113-121 (In French).

219. Verma, K. S. (2008). World perspective on short rotation forestry. In Proceedings of National Symposium on *'Intensive forest farming: The State of the Art'* held during Feb 12-14, 2008 at PAU, Ludhiana.1-2 pp.

220. Vertannen, A., Johansson, S. G., Kaarakka, V., Sarajarvi, I. and Sarkeala, J. (1993). Biomass equations for *Acacia reficiens*, *Acacia zanziberica* and *Prosopis juliflora*, and volume equations for *Eucalyptus camaldulensis* and *Terminalia brownii. East African Agricultural and Forestry Journal.* 58: 13-21.

221. Volk, T. A., Abrahamson, L. P., Nowak, C. A., Smart, L. B., Tharakan, P. J. and White, E. H. (2006). The development of short-rotation willow in the north-eastern United States for Bioenergy, bioproducts, agroforestry and phytoremedation. *Biomass and Bioenergy*. 30: 715-7.

222. Weber, R. (1891). *Textbook of forest management with emphasis on tree growth.* Springer-Verlag, Berlin.

223. Whittaker, R. H. and Woodwell, G. M. (1968). Dimension and production relations of trees and shrubs in the Brookhaven Forest, New York. *Journal of Ecology*. 56: 1–25.

224. Wiensczyk, A. M., Dumas, M. T. and Irwin, R. N. (1997). Predicting *Armillaria ostoyae* infection levels in black spruce plantations as a function of environmental functions. *Canadian Journal of Forest Research*. 27: 1630-1634.

225. Wilkinson, L. and Coward, M. (2007). Systat: Statistics-II. (Version 12) [Computer software]. Systat software Inc, Sanjose, CA-95110.

226. Williams, M. (1997). A regression technique accounting for heterosedastic and asymmetric errors. *Journal of Agricultural, Biological and Environmental Statistics*. 2: 108-129.

227. Winson, C. P. (1932). The Gompertz curve as a growth curve. *Proceedings of National Academy of Sciences*. 18: 1-8.

228. Wirth, C., Schumacher, J. and Schulze, E. D. (2004). Generic biomass functions for Norway spruce in central Europe—a metaanalysis approach toward prediction and uncertainty estimation. *Tree Physiology*. 24: 121–139.

229. Yuancai, L, Marques, C. P. and Bento, J. M. (2001). Simultaneous modeling of stand volume yield, dominate height and basal area growth models. *Journal of Forest Science*. 47: 285-293.

230. Yuancai, L., Marques, C. P. and Bento, J. M. (2000). Elasticity analysis of forest growth and yield models: a case of eucalyptus plantations in central-interior Portugal. *Journal of Forest Science*. 46: 497-505.

231. Zeide, B. (1992). Analysis of growth equations. *Forest Science*. 39: 594-616.

232. Zhang, Y., Borders, B., Will, R., and Posadas, H. (2004). A model for foliage and branch biomass prediction for intensively managed fast growing loblolly pine. *Forest Science*. 50: 65-80.

233. Zianis, D. and Menuccini, M. (2003). On simplifying allometric analyses of forest biomass. *Forest Ecology and Management*. 187: 311-332.

234. Zianis, D., Muukkonen, P., Makipa, R. and Mencuccini, M. (2005). Biomass and stem volume equations for tree species in Europe. *Silva Fennica Monographs*. No. 4, 63 pp.

235. Zullinger, E. M., Ricklefs, R. E., Redford, K. H. and Mace, G. M. (1984). Fitting sigmoidal equations to mammalian growth curves. *Journal of Mammology*. 65: 607-636.

236. Zweifel, J. R. and Lasker, R. (1976). Prehatch and posthatch growth of fishes- a general model. *Fish Bulletin*. 74: 609-621.

Annexures

Annexure. 1: HTML source code of the homepage of Tree Growth Modelling Website.

```
<!DOCTYPE HTML PUBLIC "-//W3C//DTD HTML 4.01 Transitional//EN"
"http://www.w3.org/TR/html4/loose.dtd">
<html>
<head>
<title>Welcome to Tree Growth Modelling: Indian Experiences</title>
<meta http-equiv="Content-Type" content="text/html; charset=iso-8859-1">
<style type="text/css">
<!--
.style1 {
        color: #FFFFFF;
        font-weight: bold;
        font-size: 24px;
}
.style2 {font-size: 16px}
.style10 {color: #006633; font-weight: bold; font-size: 12px; }
.style21 {
        color: #336633;
        font-family: "Times New Roman", Times, serif;
        font-size: 12px;
}
body {
        background-color: #FFFFFF;
        background-image: url(images/ACEXPDTN-ed.jpg);
}
.style11 {
        color: #FFFFFF;
        font-size: 12px;
}
a:link {
        color: #336633;
}
a:visited {
        color: #336633;
}
.style15 {color: #336633; font-family: "Times New Roman", Times, serif; font-size: 12px; }
.style22 {font-size: 10px; color: #006600; font-weight: bold; }
.style23 {
        color: #336633;
        font-size: 12px;
}
.style24 {      font-size: 16px;
        font-weight: bold;
```

```
}
.style4 {color: #000000}
.style25 {color: #006633}
.style27 {font-size: 12px}
.style30 {font-size: 32px}
.style34 {font-size: 20px}
.style36 {
        font-size: 12px;
        color: #336633;
        font-weight: bold;
}
.style38 {font-size: 14px}
.style39 {color: #006600}
.style41 {
        font-size: 12px;
        font-weight: bold;
        color: #006600;
}
-->
</style>
</head>

<body>
<table width="803" border="0" align="center">
  <tr>
    <td width="69" height="88"><img src="images/LogoNRC1.jpg" width="81" height="85"
align="top"></td>
    <td width="660" valign="middle" bgcolor="#2B5500"><p align="center" class="style1
style27"><span class="style30">Tree Growth Modelling: Indian Experiences<br>
    </span>
        <span class="style34">National Research Centre for Agroforestry, Jhansi
(NRCAF)</span><br>
        <span class="style38">Indian Council of Agricultural Research, New Delhi
(India)</span> </p>    </td>
    <td width="60" valign="top"> <img width="79" height="86"
src="index_clip_image002.gif"></td>
  </tr>
</table>

<table width="802" border="0" align="center">
  <tr>
    <td width="246" valign="top" bgcolor="#FFFFCC"><table width="246" border="0">
      <tr>
        <td background="images/ACRICEPR.GIF"><img src="images/fern-16.gif" width="16"
height="16"></td>
```

```
        <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u><a href="modelling.htm">Definition of modelling
</a></u></span></td>
      </tr>
      <tr>
        <td background="images/ACRICEPR.GIF"><img src="images/fern-16.gif" width="16"
height="16"></td>
        <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u><a href="types.htm">Types of modelling</a> </u></span></td>
      </tr>
      <tr>
        <td background="images/ACRICEPR.GIF"><img src="images/fern-16.gif" width="16"
height="16"></td>
        <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u><a href="model%20development.htm">Model Development
process</a> </u></span></td>
      </tr>
      <tr>
        <td background="images/ACRICEPR.GIF"><img src="images/fern-16.gif" width="16"
height="16"></td>
        <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u><a href="modelling%20techniques.htm">Tree Growth Modelling
Techniques</a> </u></span></td>
      </tr>
      <tr>
        <td background="images/ACRICEPR.GIF"><img src="images/fern-16.gif" width="16"
height="16"></td>
        <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style36"><u><a href="relevant%20models.htm">Models Relevant to
agroforestry</a></u></span></td>
      </tr>
      <tr>
        <td background="images/ACRICEPR.GIF"><img src="images/fern-16.gif" width="16"
height="16"></td>
        <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u>Model Refinement</u></span></td>
      </tr>
      <tr>
        <td background="images/ACRICEPR.GIF"><img src="images/fern-16.gif" width="16"
height="16"></td>
        <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u>Data simulation </u></span></td>
      </tr>
      <tr>
        <td width="16" background="images/ACRICEPR.GIF"><img src="images/fern-16.gif"
width="16" height="16"></td>
```

```
        <td width="220" background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><a href="TGM-Publications.htm">TGM Publications </a></span></td>
      </tr>
    </table>
      <table width="244" border="0">
        <tr>
          <td width="238"><img src="images/anigif-1.gif" width="237" height="178"></td>
        </tr>
      </table>
      <table width="242" border="0">
        <tr>
          <td width="18"><img src="images/fern-16.gif" width="16" height="16"></td>
          <td width="214" background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u><a href="feedback.html">Feedback </a></u></span></td>
        </tr>
        <tr>
          <td><img src="images/fern-16.gif" width="16" height="16"></td>
          <td background="images/cream2[1].gif" bgcolor="#FFFFCC"><span
class="style10"><u><a href="Contact%20us.htm">Contact us </a></u></span></td>
        </tr>
      </table>    </td>
      <td width="291" bgcolor="#FFFFCC"><p align="justify" class="style21">This site
entitled &quot;Tree Growth Modelling: Indian Experiences&quot; has been designed with
the basic objective of providing a platform where the user can have the basic concepts used in
development of tree growth models at one end and the comprehensive collection of already
developed model for a specfic tree species at other end so as to use them directly for
prediction purposes. There are a number of fast growing tree species like Eucalyptus Poplus
etc. That have been widely accepted by the Indian farmers in agroforestry/block plantations.
The basic reason for adoption being the short rotation nature which provides farmers
substantial returns at early age.Keeping these considerations in mind, at the initial phase of
development of this site,we have concentrated on Eucalyptus species modelling only because
of two reasons:Firstly NRCAF is underway on execution of a mega project on Eucalyptus
based systems for semi arid regions of India and secondly this forms a part of the Ph.D.
programme of my research scholar working on &quot;Documentation, analysis and
modelling of Eucalyptus based system for development of consolidated models at Zonal /
National level&quot;. However other important agroforestry species like Poplar, Casuarina,
Neem, Albizzia <span class="style15"> etc. </span>and biofuel species will be added in near
future.</p>
        <p align="right" class="style15"><strong>
        Dr.Ajit</strong></p></td>
        <td width="251" valign="top" bgcolor="#FFFFCC"><table width="248" border="0">
          <tr>
            <td colspan="2">
              <div align="center" class="style10">Eucalyptus Modelling </div></td>
          </tr>
          <tr>
```

```
      <td><img src="images/green.gif" width="12" height="12"></td>
      <td background="images/cream2[1].gif" bgcolor="#FFFFCC" class="style10"><u><a
href="Introduction.htm">Eucalyptus Introduction</a></u></td>
    </tr>
    <tr>
      <td><img src="images/green.gif" width="12" height="12"></td>
      <td background="images/cream2[1].gif" bgcolor="#FFFFCC" class="style10"><u><a
href="Biomass-models.htm">Published Biomass Equations in India </a></u></td>
    </tr>
    <tr>
      <td><img src="images/green.gif" width="12" height="12"></td>
      <td background="images/cream2[1].gif" bgcolor="#FFFFCC" class="style10"><u><a
href="Volume-Models.htm">Published Volume Equations in India</a></u></td>
    </tr>
    <tr>
      <td><img src="images/green.gif" width="12" height="12"></td>
      <td background="images/cream2[1].gif" bgcolor="#FFFFCC" class="style10"><u><a
href="References.htm">References</a></u></td>
    </tr>
    <tr>
      <td width="12"><img src="images/green.gif" width="12" height="12"></td>
      <td width="226" background="images/cream2[1].gif" bgcolor="#FFFFCC"
class="style10"><u><a href="eucalyptus%20images.htm">Photo Gallery </a></u></td>
    </tr>
  </table>
    <table width="200" border="0">
      <tr>
        <td><img src="images/anigif-2.gif" width="237" height="178"></td>
      </tr>
    </table>
    <table width="249" border="0">
      <tr>
        <td bgcolor="#FFFFCC"><span class="style10">Last Updated: 10-06-
2008</span></td>
      </tr>
      <tr>
        <td width="243" height="59"><p align="center"><strong>No.of hits <br>
          0 0 0 0
        </strong></p>
          <p><span class="style22"><font color="#006600" size="1"><b><font
size="1"><b><font size="1"></font></b></font></b></font></span></p></td>
      </tr>
    </table></td>
  </tr>
</table>
<table width="801" border="0" align="center">
```

```html
<tr>
  <td width="608" background="images/cream2[1].gif" bgcolor="#FFFFFF"><span
class="style2"><strong><span class="style24"><span class="style13 style23
style5">Website: Designed, <strong><span class="style13 style11
style25">Compiled</span></strong> and Maintained by Dr. Ajit &amp; <strong> <a
href="Nighat-CV.pdf" class="style4">Nighat Jabeen</a></strong>, NRCAF,Jhansi<br>
    Supervision &amp; Guidance: Dr. S.K.Dhyani, Director, NRCAF,Jhansi , <span
class="style13 style2 style11 style39"><span class="style13
style27"><strong>Copyright&copy;2008NRCAF,Jhansi</strong></span></span></span></s
pan></strong></span></td>
  <td width="183" background="images/cream2[1].gif" bgcolor="#FFFFFF"><span
class="style41"><a href="file:///C|/net/index.htm">Back to INARIS </a></span></td>
 </tr>
</table>
<p> </p>
</body>
</html>
```

NATIONAL SYMPOSIUM
on
AGROFORESTRY KNOWLEDGE FOR SUSTAINABILITY, CLIMATE MODERATION AND CHALLENGES AHEAD
15 – 17 DECEMBER, 2008

NATIONAL RESEARCH CENTRE FOR AGROFORESTRY, JHANSI - 284 003
e.mail:orgsec@gmail.com, Phone: 2730214(Off), 09415179658 (M), Fax: (0510) 2730364

Ref: Nat Sym/Abst   Date:06 October 2008

To
Ms. Jabeen

Sub. : Acceptance of your abstract for presentation during National Symposium on **"Agroforestry Knowledge For Sustainability, Climate Moderation and Challenges Ahead"**

I am happy to inform you that abstract submitted by you for presentation during National Symposium on **"Agroforestry Knowledge For Sustainability, Climate Moderation and Challenges Ahead" from 15 – 17 DECEMBER, 2008** at NRCAF, Jhansi has been accepted. The mode of presentation will be Poster. You are requested to prepare full length paper as per the guidelines provided with the first circular. You are also requested to send your registration fee, full length paper and travel programme at the earliest to the organizing secretary. The organizing committee is looking forward for your valuable participation in the National Symposium. The topic and theme of your abstract is as under :

Generalized models for prediction of aboveground biomass for Eucalyptus species in India in the theme 1.4 as per detailed in the circular of the symposium.

With kind regards,

Yours Sincerely

AHanda

(A.K. Handa)
Organizing Secretary

Ms. Nighat Jabeen
Student
National Research Centre For Agroforestry Jhansi 284003, UP

NATIONAL SYMPOSIUM

on

AGROFORESTRY KNOWLEDGE FOR SUSTAINABILITY, CLIMATE MODERATION AND CHALLENGES AHEAD

15 – 17 DECEMBER, 2008

NATIONAL RESEARCH CENTRE FOR AGROFORESTRY, JHANSI - 284 003

e.mail:orgsec@gmail.com, Phone: 2730214(Off), 09415179658 (M), Fax: (0510) 2730364

Ref: Nat Sym/Abst **Date:06 October 2008**

To
Ms. Jabeen

Sub. : Acceptance of your abstract for presentation during National Symposium on **"Agroforestry Knowledge For Sustainability, Climate Moderation and Challenges Ahead"**

I am happy to inform you that abstract submitted by you for presentation during National Symposium on **"Agroforestry Knowledge For Sustainability, Climate Moderation and Challenges Ahead" from 15 – 17 DECEMBER, 2008** at NRCAF, Jhansi has been accepted. The mode of presentation will be Poster. You are requested to prepare full length paper as per the guidelines provided with the first circular. You are also requested to send your registration fee, full length paper and travel programme at the earliest to the organizing secretary. The organizing committee is looking forward for your valuable participation in the National Symposium. The topic and theme of your abstract is as under :

Designing and popularizing tree growth modelling website in Indian perspective in the theme 1.4 as per detailed in the circular of the symposium.

With kind regards,

Yours Sincerely

AHanda

(A.K. Handa)
Organizing Secretary

Ms. Nighat Jabeen
Student
National Research Centre For Agroforestry Jhansi 284003, UP

NATIONAL SYMPOSIUM

on

AGROFORESTRY FOR LIVELIHOOD SECURITY, ENVIRONMENT PROTECTION & BIOFUEL PRODUCTION

16-18 DECEMBER, 2006

Abstracts

Organised by

INDIAN SOCIETY OF AGROFORESTRY

AND

NATIONAL RESEARCH CENTRE FOR AGROFORESTRY

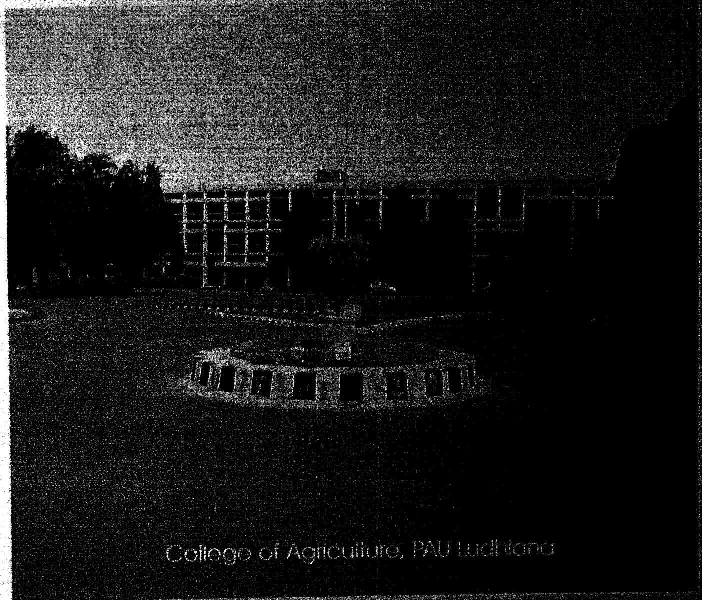
JHANSI - 284 003

treatment, 40 kg N/ha, 60 kgP_2O_5/ha, 40 kg N+ 60 kg P_2O_5/ha and 40 kg N+ 60 kg P_2O_5/ha+bacteria seed inoculation. Altogether 18 treatment combinations were applied in randomised block design with three replications. The observations on growth parameters *viz.* plant height, dry matter production per plant, tillers/plant in cenchrus and branches/plant in cowpea were recorded at harvest. Besides this growth attributing parameters in aonla tree were recorded on plant height, canopy diameter and DBH at quarterly. The green and dry fodder yield was recorded at physiological maturity and 50% flowering stage of crop growth for each treatment. The crude protein content in dry matter of both crops was estimate by micro Kjeldahl method. The mean data analysis for three years revealed that plant height, dry matter accumulation, number of tillers/plant in cenchrus and branches in cowpea and seed yield/plant in *Cenchrus* and cowpea were significantly increased with different intercropping row ratios of both the crops. However, maximum increase was with 1:1 row ratio followed by 1:2 and 2:1 row ratios, respectively. Similarly, green fodder, dry matter production and seed yields were increased remarkably under all the intercropping systems, except seed yield of cowpea under 1:2 and 2:1 intercropping systems. Integrated nutrient management had also significant effects on the growth parameters *viz.* plant height, DMA/plant, tillers/plant and seed yield /plant in *Cenchrus* and number of branches/ plant and seed yield /plant of cowpea under aonla based hortipastoral system. However, the variation among the treatments with each other was remained at par for all the growth parameters except the treatments with seed inoculation and application of 40 kg N+ 60 kg P_2O_5/ha+ bacterial seed inoculation. Higher values of green fodder and dry matter production were obtained under 1:1 row ratio of cenchrus and cowpea as compared to 1:2 and 2:1. But the higher seed yield and protein content were obtained with 1:2 row ratio followed by 1:1 and 2:1 row ratios. Application of 40 kg N/ha+60 kg P_2O_5/ha along with seed inoculation gave maximum production of green fodder, dry matter, seed yield and protein content than other treatments combinations, the next best treatment was when nitrogen and phosphorus were applied together. It can be concluded that judicious usage of biofertilizers together with nitrogen and phosphorus have better results in grass-legume mixed pasture as compared to their independent use. The aonla based intercropping system of cenchrus and cowpea is a suitable alternative technique of hortipastoral system for higher fodder, food and fruit production in semi arid areas.

COMPARISON OF INITIAL GROWTH AND YIELD OF *EUCALYPTUS TERETICORNIS* CLONES UNDER AGROFORESTRY SYSTEM VIS-À-VIS BLOCK PLANTATIONS IN SEMI-ARID CONDITIONS OF INDIA

Ajit, Ritu, Nighat Jabeen, Rajender Singh, A.K.Handa, Ram Newaj and O.P.Chaturvedi
National Research Centre for Agroforestry
Gwalior Road, Jhansi-284003 (UP), India
E.mail: umaajitgupta@yahoo.co.in; umaajitgupta@rediffmail.com, ajit@mail.nrcaf.ernet.in

An experiment for growth and yield analysis/modeling of Eucalyptus based systems in Bundelkhand region was initiated at NRCAF, Jhansi with four clones of *Eucalyptus tereticornis* (C-3, C-6, C-7 and C-10 obtained from ITC Bhadrachalam, Andhra Pradesh) in different systems and spacing, namely agrisilviculture (5x4, 10x2, 10x5, 8x4, 5x5 m), compact block (3x3, 2.5x2.5 m) and boundary plantations (2.5m). The growth observations were recorded after every three months in the first year and after six month in second year onwards. Observed parameters include total height, DBH, CD and canopy of the each individual tree. A total of 1335 trees from the complete experiment were measured for the first year. However, from second year only 510 trees were marked from the whole experiment for further growth observation. Eight trees (two from each clone) were selected from compact block plantation of spacing 2.5 x 2.5 m and other eight were harvested from agrisilviculture



College of Agriculture, PAU Ludhiana

Organiser

Department of Forestry and Natural Resources, PAU Ludhiana - 141 004

Sponsor

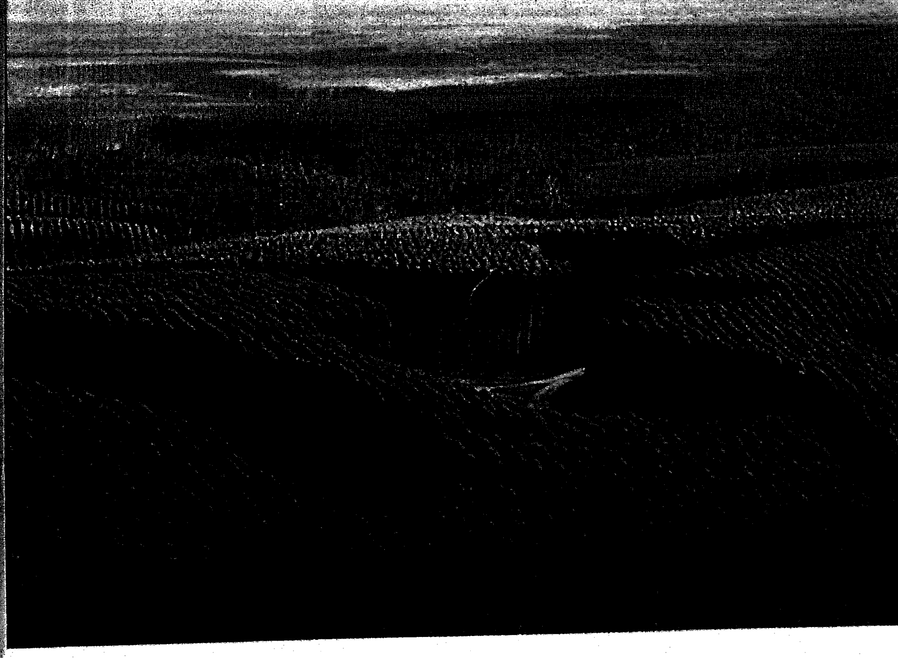
Indian Counci of Forestry Research and Education, Dehradun -248 006

NATIONAL SYMPOSIUM

ON

INTENSIVE FOREST FARMING: THE STATE OF THE ART

(February 12-14 , 2008)



Organiser

Department of Forestry and Natural Resources

Punjab Agricultural University, Ludhiana -141 004

Sponsor

Indian Council of Forestry Research and Education, Dehradun -248 006

STATISTICAL PREDICTION OF HEIGHT THROUGH HEIGHT/DIAMETER MODELS FOR *EUCALYPTUS TERETICORNIS* IN CENTRAL INDIA

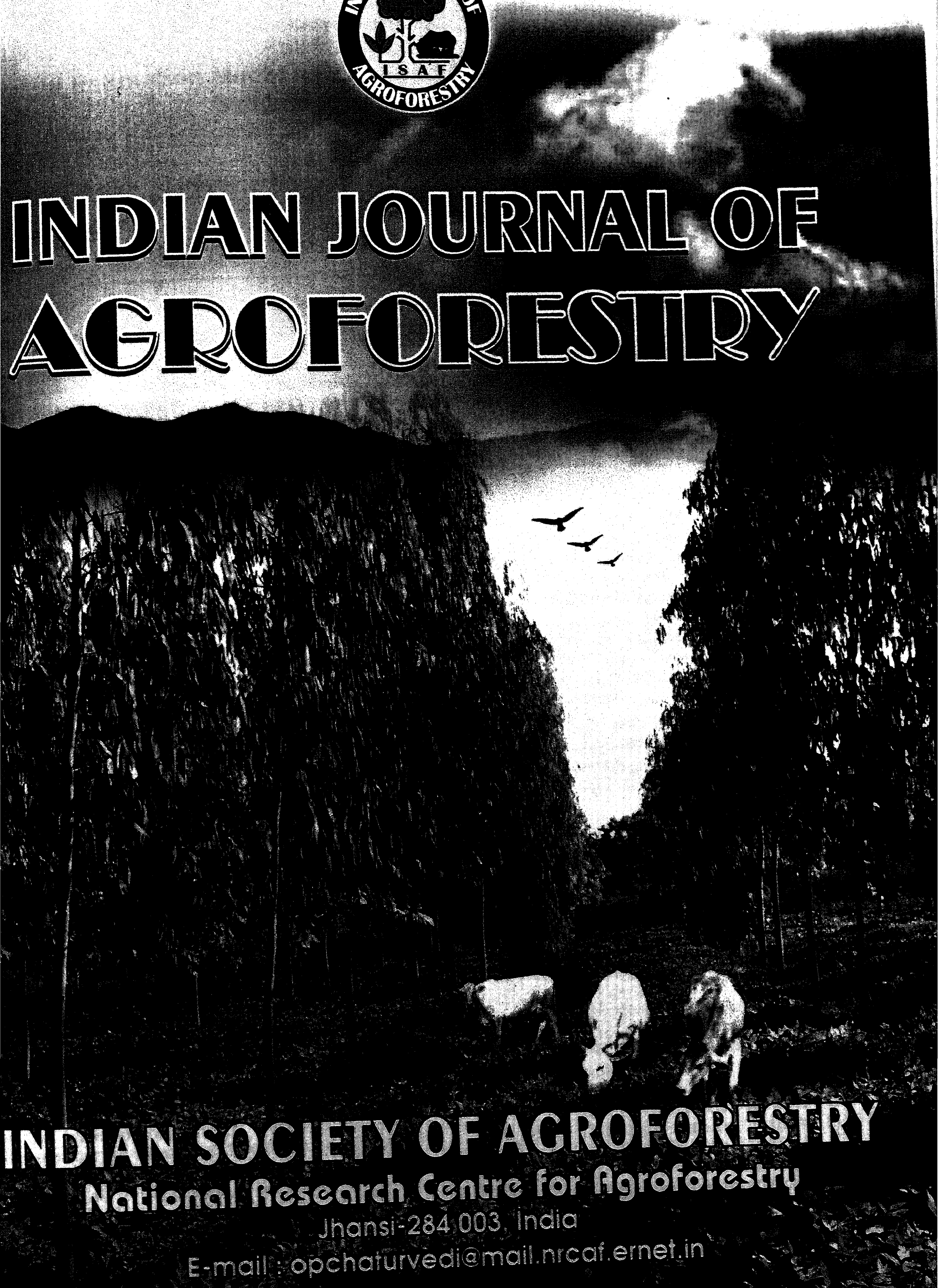
AJIT, RITU, N. JABEEN, A.K. HANDA AND
O.P. CHATURVEDI
NRCAF-Jhansi (UP) - 284 003
(ajit@nrcaf.ernet.in)

An experiment was initiated for the structural analysis and modelling of *Eucalyptus* based system at NRCAF, Jhansi during August, 2003 with the objective of studying the structure, biomass, productivity and modelling the growth of *Eucalyptus* based systems. The experiment was laid with three systems of *Eucalyptus tereticornis* namely agrisilviculture, block plantation and boundary plantation. Tree spacings considered in agrisilviculture were 5m x 4m, 10m x 2m, 10m x 5m, 8m x 4m and 5m x 5m ; compact block are 3m x 3m and 2.5m x 2.5m and boundary plantation is 2.5 m. Wheat and blackgram were grown in the interspaces during rabi and kharif seasons, respectively. Four *Eucalyptus* clone namely C-3, C-6, C-7 and C-10 were obtained from ITC, Bhadrachalam and planted on 15th August, 2003. In this article, the development and validation of height-diameter models have been reported. Growth observations (diameter at breast height and height) were recorded quarterly in the first year and twice a year in the subsequent period. The MAI (Mean annual increment) of height and dbh was 4.01m and 4.2cm, respectively at the age of three years. Infact, it becomes extremely tedious to accurately measure the height of large trees (more than 10 mt), whereas, the dbh (diameter at 1.37m height) can be easily measured and accordingly height-diameter models provide a handy tool for prediction of height on the basis of dbh values. The data recorded on diameter and height of marked trees for a period of two years (with more than 4400 observations) was initially used for developing height-diameter model. Allometric function was fitted to the observed data and the fitted function was of the form $\mathbf{Y=209.93* X^{0.709}}$ (with $\mathbf{R^2=0.96}$), where Y is the height and X is diameter at breast height (X and Y are both measured in cm). With the objective of validating this model (developed utilizing the growth data of initial two years), the growth data of the 3rd year was clubbed with the initial 2 years data set and the resulting data set consisting of more than 5300 observations was used to develop the model and the resultant fitted allometric function was of the form $\mathbf{Y=212.80* X^{0.715}}$ (with $\mathbf{R^2=0.96}$), where Y is the height and X is diameter at breast height (X and Y are both measured in cm). The comparison of model parameters clearly revealed that the model developed utilizing three years data is almost the same as the model developed utilizing initial two years data and thus confirms the stability of the model. The proposed model can be used for predicting the height of standing trees without destructive harvesting, by simply measuring the diameter at breast height.

Keywords: Statistical prediction, height, model, central India

UME 10 NO. 2, 200

INDIAN JOURNAL OF AGROFORESTRY



INDIAN SOCIETY OF AGROFORESTRY

National Research Centre for Agroforestry

Jhansi-284 003, India

E-mail : opchaturvedi@mail.nrcaf.ernet.in

Indian J. of Agroforestry Vol. 10 No. 2 : 34 - 39 (2008)

Height Estimation Model for *Eucalyptus tereticornis* Grown under Semiarid Conditions of India

Ajit, Ritu Srivastava, Nighat Jabeen, A.K. Handa, Rajendra Singh and O.P. Chaturvedi

National Research Centre for Agroforestry
Gwalior Road, Jhansi-284003 India

ABSTRACT

An experiment on structural analysis and modelling of Eucalyptus based system was initiated at NRCAF, Jhansi in 2003 with three systems (agrisilviculture, block plantation and boundary plantation) and four clones obtained from ITC Bhadrachalam. To estimate the height of large trees, three types of models viz Richards, Schumacher, Allometric were attempted with dbh as predictor and the R^2 values were almost comparable in the three systems. However, when these models were extrapolated to examine their behaviour outside the observed range of dbh, the allometric function resulted in reasonably acceptable predictions even quite outside the observed range also, whereas the other two namely Richards and Schumacher leads to merely constant estimation for the extrapolated region. Accordingly, the allometric models are proposed for estimating the height values by simply measuring the dbh of the standing Eucalyptus trees in these systems.

Key words: *Eucalyptus, height diameter models, allometric equations, validation*

1. INTRODUCTION

In forestry, mathematical equations form the basis of many prediction studies. Typical example of such equation are height prediction model based on diameter, such models gain importance as modern scientific management relies heavily on well defined growth and yield models that can be used to access the status of stands at any point of time. *Eucalyptus tereticornis* being exotic to India, its cultivation has spread to nearly the whole of the Indian subcontinent. Large-scale plantations of *E. tereticornis* were established between 1970 and 1985. Nearly 2% of the cultivable land in northwestern India is planted with *E. tereticornis*.The average productivity of *E. tereticornis* plantations is 10 m^3/ha/year on forestlands and 15-20 m^3/ha/year on farmlands. The average productivity of commercial clones is about 20-25 m^3/ha/year and many farmers have achieved up to 50 m^3/ha/year. Infact, for the computation of productivity of such plantations, precise measurements of growth attributes (height and diameter) are essential. It has been noticed during the course of experimentation that it becomes extremely tedious to accurately measure the height of large trees (more than 10 meter), whereas the dbh (diameter at 1.37m height) can be easily measured and accordingly height-diameter models provide a handy tool for prediction of height on the basis of dbh values. Recently height-diameter curves have been frequently developed in forestry studies (Sharma and Parton, 2007; Lootens *et al.*, 2007; Casteo *et al.*, 2006; Reed *et al.*, 2003; Mehtatalo, 2005; Inoue and Yoshida, 2004; Sochacki *et al*, 2007). Bachpai *et al.*, 2005 developed multiple regression models for prediction of height using dbh and age for *Bambusa tulda* Roxb. plus clumps in regions of Assam and Meghalaya. Tiwari and Gadow, 2003 developed a height-diameter relationship for *Prosopis cineraria* for the hot arid areas of India. Tewari *et al.*, 2002, have attempted height-age and diameter-age for irrigated plantation of Rajasthan; Soares and Tome, 2002, have developed height-diameter equation for *Eucalyptus* in first rotation.

Present study deals with the development of height-dbh model under different systems, utilizing the data of initial years of growth, for application to a much wider range (viz maturity and even senescence age).

2. MATERIALS AND METHODS

2.1 Study site and experimental details

The experiment is being carried out at the Central Research Farm of National Research Centre for Agroforestry, Jhansi which is located at an elevation of 300 m above sea level and is situated between 24°11' N latitude and 78°17' E longitude having tropical semi arid climate with mean annual rainfall of 900 mm. More than 75% of the rainfall is received during monsoon season (last week of June to first week of September). Mean maximum temperature ranges from 47.4° C (June) to 23.5° C (December) and mean minimum temperature from 27.2° C (June) to 4.1° C (December). The soil of the experimental area is sandy loam with low organic carbon, nitrogen, phosphorous and medium to high in potassium. The study was initiated in

August, 2003 with the objective of studying the structure, biomass, productivity and modelling the growth of Eucalyptus based systems. The experiment was laid with three systems of *Eucalyptus tereticornis* namely agrisilviculture (AS), block plantation (CB) and boundary plantation (BP). Tree spacings considered in agrisilviculture are 5x4 m, 10x2 m, 10x5 m, 8x4 m and 5x5 m; compact block are 3x3 m and 2.5x2.5 m and boundary plantation is 2.5 m. Wheat and Black gram were grown in the interspaces during Rabi and Kharif seasons respectively under boundary plantations and agrisilviculture systems. Four Eucalyptus clone namely C-3, C-6, C-7 and C-10 were obtained from ITC, Bhadrachalam (A.P.) and planted in field during August, 2003. In this article, the development and validation of height-diameter models have been reported. Growth observations (dbh-diameter at breast height and height) were recorded quarterly in the first year and twice a year in the subsequent period.

2.2 Data and observations

The available data includes the tree wise observations on height in meter taken from the ground level to tip of the shoot of the main bole and dbh (diameter at breast height) in centimeter taken at a height of 1.37m at the main bole) for a period of 28 months. During the first year, observations were recorded four times in a year on 1335 trees distributed over the three systems viz agrisilviculture, compact block and boundary plantation. Whereas from second year onwards observations were recorded twice a year on 510 selected trees distributed proportionally over the three systems.

2.3 Statistical analysis and candidate function

Systat software (Wilkinson *et al.*, 1996) was used for computation of descriptive statistics (mean, SD, skewness, kurtosis etc) and fitting of non-linear equations (estimates of model parameters, asymptotic standard error of estimate, confidence interval, R^2 values) and plotting of various graphs pertaining to residual diagnostics and model validation (probability plot of residuals, auto correlation plots etc.)

The following functions were attempted to fit the observed data

Name of function	Functional form	Parameter interpretation
Allometric	Height = $a^*(DBH)^b$	a = Scaling parameter
		b = Power coefficients
Richards	Height $=a^*[1-\exp(-k^*DBH)]^{(1/1-m)}$	a = Asymptote
		k = Rate of approach to the asymptote
		m = Shape parameter
Schumacher	Height=1.37+a*exp(-b/DBH)	a = Asymptote
		b= Shape parameter

3. RESULTS AND DISCUSSION

The observed values for height and dbh exhibited the approximate normality of variates (Table-1) under study. To get an idea of the shape of the function to be fitted on the data, a scatter plot of height vs dbh was initially drawn. It was clear from this scatter plot that the candidate functions usually adopted for modeling height-dbh curves viz Richards, Schumacher and Allometric/power will fit well the observed pooled data set(AS+CB+BP).

The parameter estimates along with other related statistics of the Richards function fitted on pooled data has been compiled in Table 2, and the resultant equation was Height=18.03*[1-exp (0.089*dbh)]$^{(1/1-0.011)}$ with R^2 (obs. vs pred.) = 0.95. Similarly the parameter estimates of schumacher and allometric functions have been compiled in Table 2, and the resultant equations were Height =1.37 + 18.95*exp (-6.79/dbh) with R^2 (obs. vs pred.) = 0.94 for schumacher and Height = 1.76*(dbh)$^{0.78}$ with R^2 (obs. vs pred.) = 0.97 for allometric functions respectively. The plots of these fitted functions along with the observed data points have been compiled in Fig.1. It is clear from the above computations and the graphs of the fitted functions that the R^2 -values are comparable for all the three functions but was obsereved to be maximum for allometric one. However, as has been pointed out by other researchers also in the recent articles (Ajit *et al.*, 2006; Prajneshu and Chandran, 2005), that R^2 value alone should not be used to judge the best fitting function and it is equally important to consider the validation and more importantly the behavior of the fitted function outside the observed range of the independent variate. Accordingly, to judge the prediction capabilities of these functions in the extrapolated region, the function curves for the three-fitted function were drawn (Fig. 2).

Table 1. Summary characteristics of growth attributes on the observed data set.

Measured variable	Average (Min, Max.)	Standard Deviation	Skewness	SE of Skewness	Kurtosis	SE of Kurtosis
Height	6.09 (1.08-14.90)	3.615	0.689	0.045	-0.55	0.090
dbh	5.04 (0.20-14.33)	3.690	0.530	0.045	-0.84	0.090

Table 2. Estimation of parameters of various functions fitted on pooled dataset (AS+CB+BP).

SN	Fitted Function	Parameter	Estimate value	Standard Error	Confidence interval Min	Confidence interval Max	R^2 value
1	Allometric	A	1.76	0.015	1.73	1.79	0.97
		B	0.78	0.004	0.78	0.79	
2	Richards	A	18.03	0.240	17.50	18.50	0.95
		K	0.089	0.001	0.08	0.09	
		M	0.011	0.009	0.00	0.03	
3	Schumacher	A	18.95	0.150	18.60	19.20	0.94
		B	6.79	0.060	6.66	6.91	

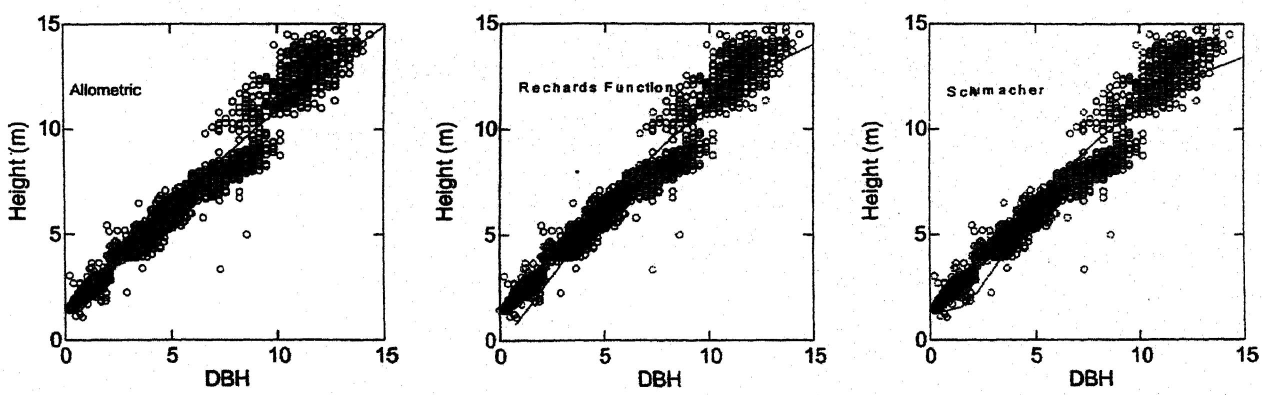


Fig.1. Different function fitted to model Height - DBH relationship on the pooled dataset (AS+BP+CB).

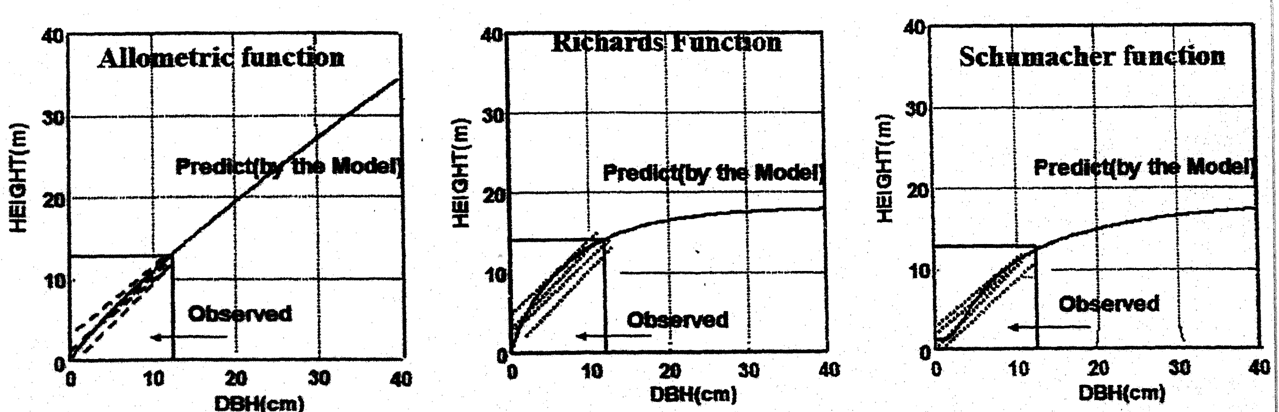


Fig.2. Extrapolated predictions of height growth with respect to DBH for different functions fitted on pooled dataset.

It is very clear from these comparative extrapolated prediction graphs of the three fitted functions that the allometric function results in reasonably acceptable estimations even quite outside the observed range also, whereas the other two namely richards and schumacher leads to merely constant estimation of size for the extrapolated range. Therefore the allometric function which meets both, the criteria's of high R^2-value and reasonably acceptable extrapolated predictions, was preferred over the other two.

To judge the accuracy of prediction, the developed allometric equation was thoroughly evaluated through residual diagnostics. The error of prediction termed as residual is computed as the difference in the observed and predicted values. Theoretically, the residual should be independently and normally attributed with mean zero and constant variance. These assumptions were evaluated through pertinent graphs (Fig.3). The plot of residuals against their expected values clearly portrayed the normality of residuals. The plot of residual vs. independent variate confined that the residual are not continuously being over/under estimated and the plot of residual against estimate indicated that the residual have constant variance. Thus the proposed allometric equation fulfilled the regression requisites.

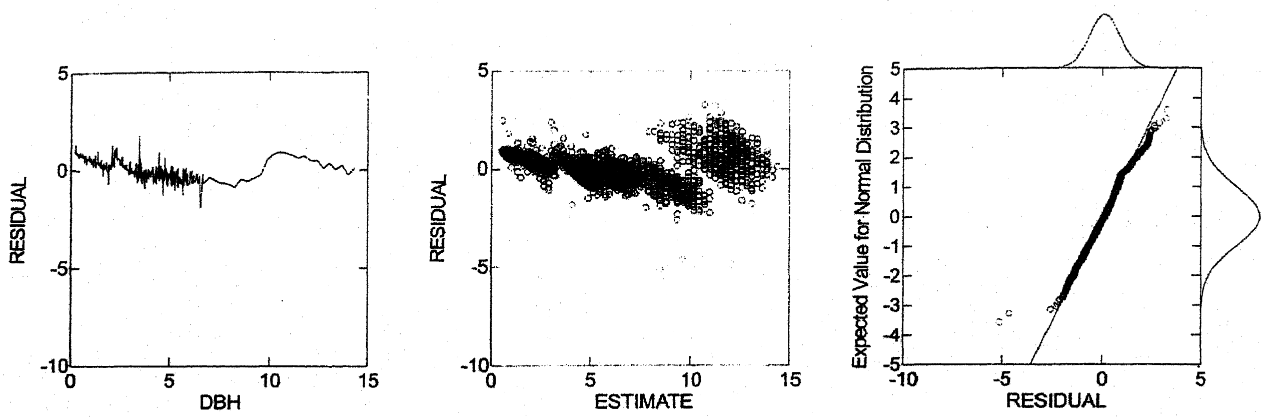


Fig. 3. Different plots of residual diagnostics for the allometric function fitted to the pooled dataset.

The allometric function for the pooled data (including all the three systems i.e AS+CB+BP) resulted in Height = 1.76*(dbh)$^{0.78}$ with R^2 (obs. vs pred.)=0.97. To compare the three systems height-DBH models based on allometric functions were also fitted separately system wise (Fig.4) and the resultant equations (Table-3)are:

Height = 1.87*(dbh)$^{0.75}$ with R^2 =0.96 for agrisilviculture

Height = 1.61*(dbh)$^{0.83}$ with R^2 =0.95 for compact block

Height = 1.65*(dbh)$^{0.81}$ with R^2 =0.97 for boundary plantation respectively.

To compute the growth performance in totality, all the three fitted allometric curves (agrisilviculture, compact block and boundary plantation), were drawn in one single frame (Fig. 5), and it is clear from this plot that growth was better in agrisilviculture for the first year, whereas compact block and boundary plantation picked up the growth in the second year. The proposed models can be used for predicting the height of standing trees at any stage without destructive harvesting, by simply measuring the diameter at breast height.

Table 3. Estimation of parameters for the allometric function fitted on individual datasets under three systems.

S.N.	System	Parameters	Estimate Value	Standard Error	Confidence Interval Minimum	Confidence Interval Maximum	R2
1	Agrisilviculture	A.	1.87	0.020	1.83	1.90	0.96
		B.	0.75	0.005	0.74	0.76	
2	Compact Block	A.	1.61	0.030	1.55	1.67	0.95
		B.	0.83	0.009	0.82	0.85	
3	Boundary Plantation	A.	1.65	0.030	1.58	1.73	0.97
		B.	0.81	0.010	0.79	0.83	

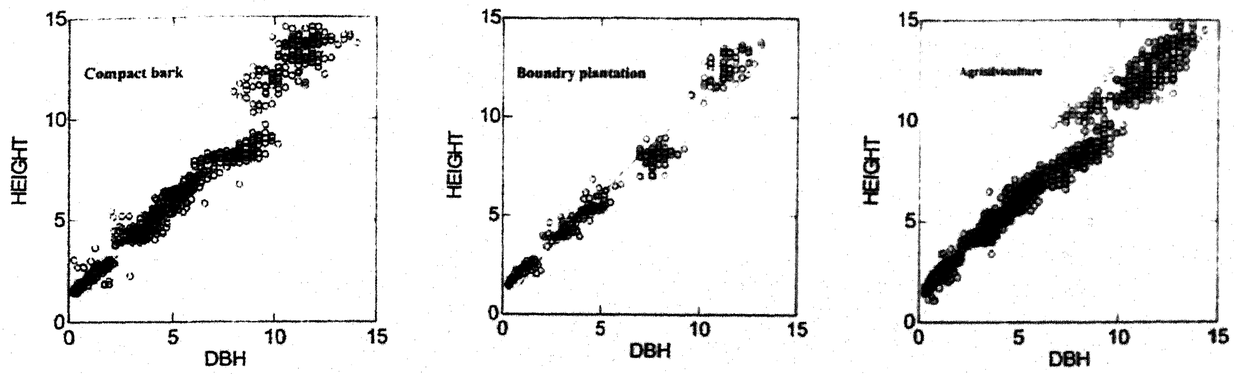


Fig. 4. Allometric function fitted on individual datasets under the three systems.

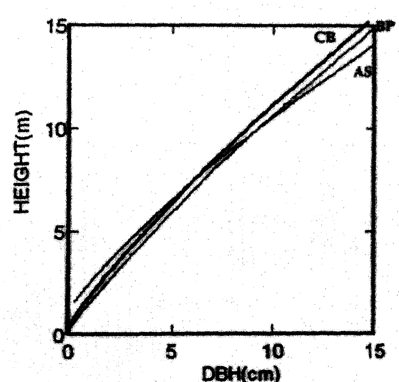


Fig 5. Comparison of the fitted allometric equation in different systems.

All used functions (allometric, richards and schumacher function) based on the criteria of R^2 (obs. vs pred.) values, gave comparable results. The allometric function lead to the reasonably acceptable predictions when these functions were validated on the criteria of extrapolated estimations outside the observed range followed by schumacher function and richards's function ranked at the last. Since model selection using nonlinear regression is an inherently subjective process, and somewhat data dependent, basing the final evaluation of the model on the validation procedure through pertinent graphs and extrapolated prediction seems to be a viable alternative when the prime objective of modeling exercise is prediction.

REFERENCES

Ajit, Rai, P., Handa, A.K., Choudhari, S. and Uma. 2006. Allometry for estimating above ground biomass of *Eucalyptus tereticornis* under energy and boundary plantations in central India. *Annals of Arid Zone* 45(2): 175-182.

Bachpai, V. K. W., Pattanaik, S., Pathak, K. C., Bhuyan, T. C., Hazarika, K., Bhattacharyya, R. and Kharshi, I. A. 2005. Studies on growth behavior of some *Bambusa tulda* Roxb. plus clumps. *Indian Forester* 131(5): 711-718.

Castedo-Dorado, F., Diéguez-Aranda, U. and Alvarez-González, J.G. 2006. A growth model for *Pinus radiata* D. Don stands in north-western Spain. *Annals of Forest Science* 64(4): 453-465.

Inoue, A. and Yoshida, S. 2004. Allometric model of the height-diameter curve for even-aged pure stands of Japanese cedar (*Cryptomeria japonica*). *Journal of Forest Research* 9(4):325-331.

Lootens, J.R., Larsen, D.R. and Shifley, S.R. 2007. Height-diameter equations for 12 upland species in the Missouri Ozark highlands. *Northern Journal of Applied Forestry* 24(2):149-152.

Mehtatalo, L. 2005. Height-Diameter models for scots pine and birch in Finland. *Silva Fennica* 39 (1): 55-66.

Prajneshu and Chandran, K. P. 2005. Competition of compound growth rates in agriculture: Revisited. *Agricultural Economics Research Review* 18: 317-324.

Reed, D. D., Jones, E. A. Tome, M. and Araujo, M. C. 2003. Models of potential height and diameter for *Eucalyptus globulus* in Portugal. *Forest Ecology and Management* 172(2-3): 191-198.

Sharma, M. and Parton, J. 2007. Heightdiameter equations for boreal tree species in Ontario using a mixed-effects modeling approach. *Forest Ecology and Management* 249(3): 187-198.

Soares, M. and Tome, M. 2002. Height - diameter equation for first rotation of Eucalyptus Plantations in Portugal. *Forest Ecology and Management* 166 (1-3): 99-109.

Sochacki, S.J., Harper, R.J. and Smettem, K.R.J. 2007. Estimation of woody biomass production from a short-rotation bio-energy system in semi-arid Australia. *Biomass and Bioenergy* 31(9): 608-616.

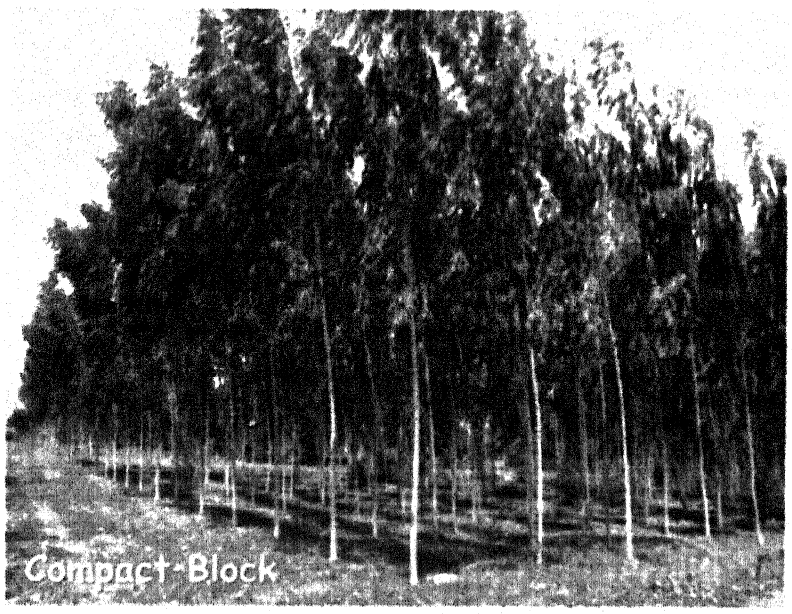
Tewari, V. P. and Gadow, K. V. 2003. Preliminary growth models for *Prosopis cineraria* (L.) Druce plantations in the hot arid region of India. *Forests Trees and Livelihoods* 13(4): 361-373.

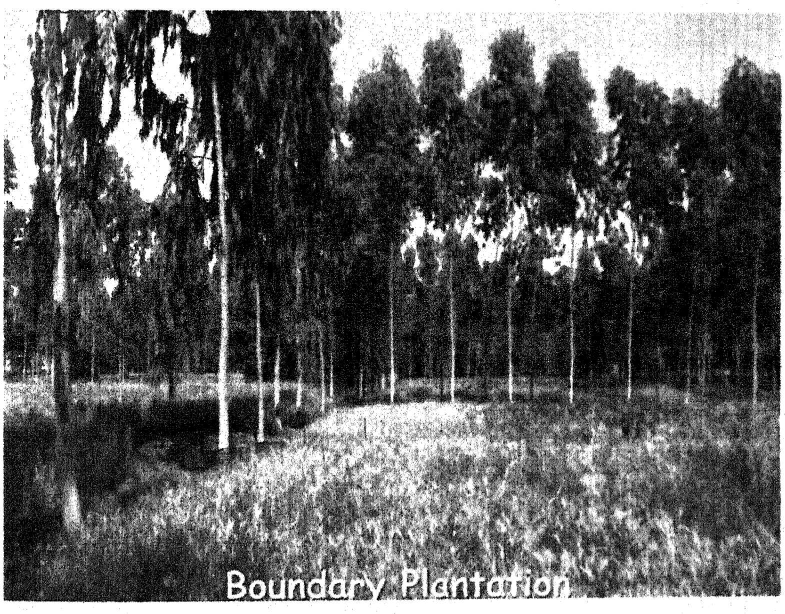
Tewari, V. P., Verma, A. and Kumar, V. S. K. 2002. Growth and yield functions for irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. *Bioresource Technology* 85· 137-146.

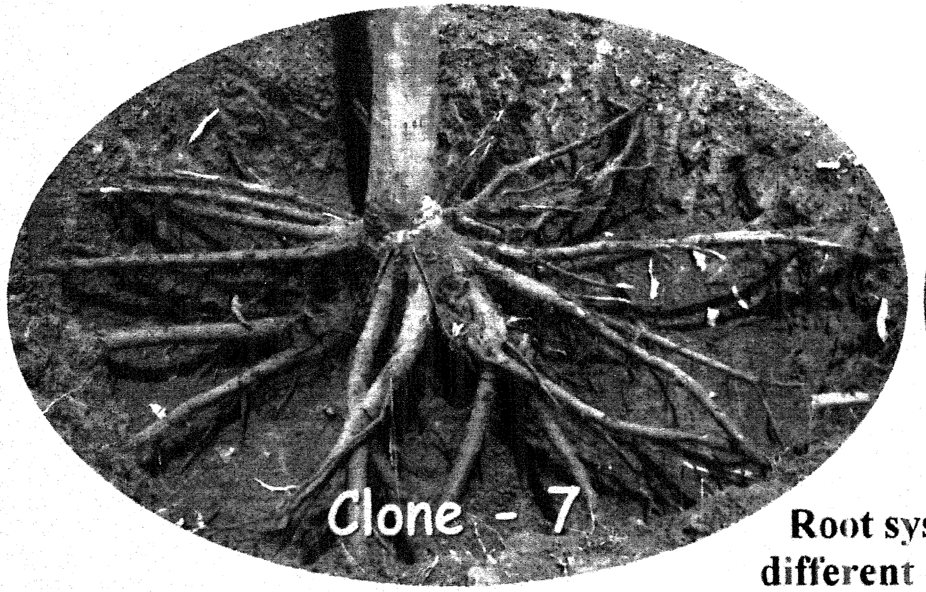
Willkinson, L, Hill, M. Welna, J.P. and Birkenbevel, B. K. 1996. SYSTAT for Windows, Version 6, SPSS Inc. Evanston, IL, USA.

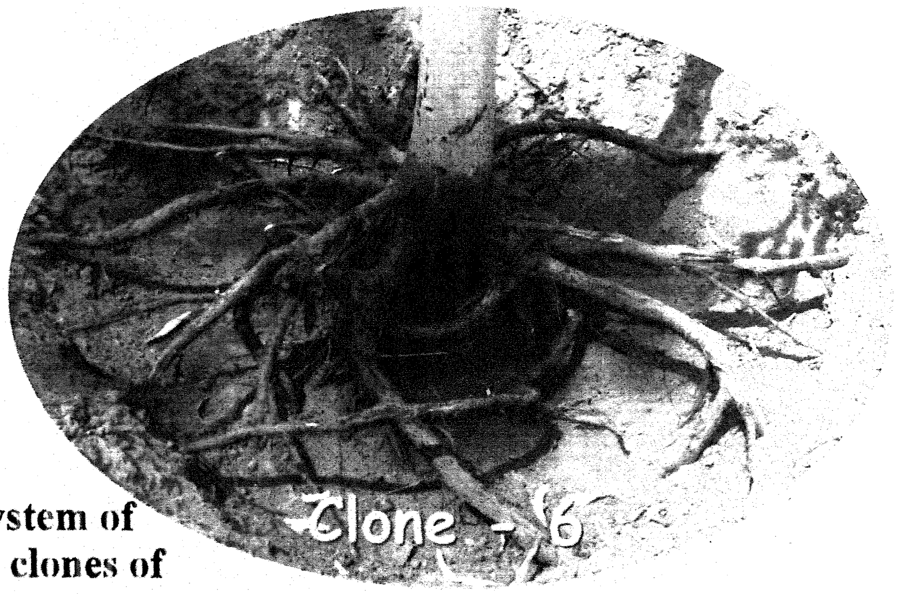
Field Photographs

Eucalyptus tereticornis **in different agroforestry systems**









Root system of different clones of *Eucalyptus tereticornis*